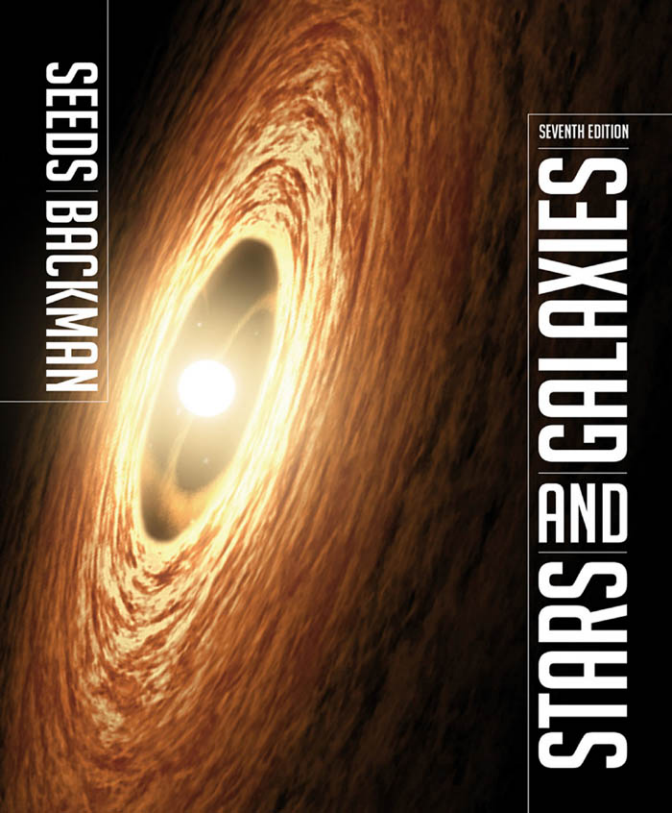


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Stars and Galaxies





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Mike Seeds has been a Professor of Physics and Astronomy at Franklin and Marshall College in Lancaster, Pennsylvania, since 1970. In 1989 he received F&M College's Lindback Award for Distinguished Teaching. Mike's love for the history of astronomy led him to create upper-level courses on "Archaeoastronomy" and "Changing Concepts of the Universe." His research interests focus on variable stars and the automation of astronomical telescopes. Mike is coauthor with Dana Backman of *Horizons: Exploring the Universe*, Eleventh Edition (2009), *Astronomy: The Solar System and Beyond*, Sixth Edition (2009), and *Perspectives on Astronomy* (2008), all published by Cengage. He was Senior Consultant for creation of the 20-episode telecourse accompanying the book *Horizons, Exploring the Universe*.

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7

SEVENTH EDITION

Stars and Galaxies

Michael A. Seeds

Joseph R. Grundy Observatory
Franklin and Marshall College

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SOFIA (Stratospheric Observatory
for Infrared Astronomy)
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Dedication

For Emery & Helen Seeds and Edward & Antonette Backman

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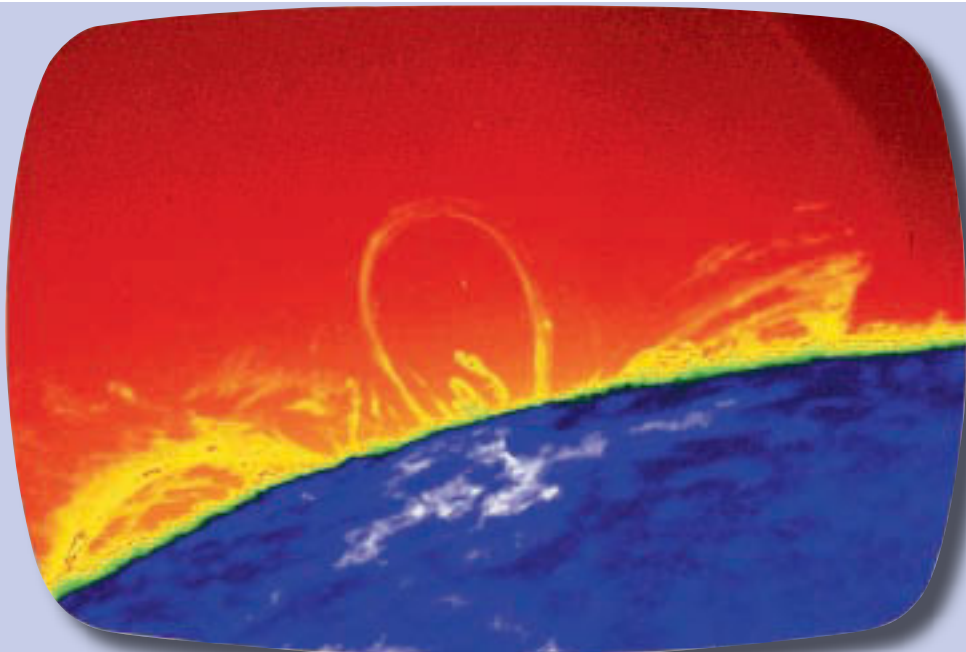
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A Note to the Student

From Mike and Dana

We are excited that you are taking an astronomy course and using our book. You are going to see some amazing things, from the icy rings of Saturn to monster black holes. We are proud to be your guides as you explore.

We have developed this book to help you expand your knowledge of astronomy from recognizing the moon and a few stars in the evening sky to a deeper understanding of the extent, power, and diversity of the universe. You will meet worlds where it rains methane, stars so dense their atoms are crushed, colliding galaxies that are ripping each other apart, and a universe that is expanding faster and faster.

Two Goals

This book is designed to help you answer two important questions:

- What are we?
- How do we know?

By the question *What are we?* we mean: How do we fit into the universe and its history? The atoms you are made of had their first birthday in the big bang when the universe began, but those atoms were cooked and remade inside stars, and now they are inside you. Where will they be in a billion years? Astronomy is the only course on campus that can tell you that story, and it is a story that everyone should know.

By the question *How do we know?* we mean: How does science work? What is the evidence, and how do you know it is true? For instance, how can anyone know there was a big bang? In today's world, you need to think carefully about the things so-called experts say. You

should demand explanations. Scientists have a special way of knowing based on evidence that makes scientific knowledge much more powerful than just opinion, policy, marketing, or public relations. It is the human race's best understanding of nature. To understand the world around you, you need to understand how science works. Throughout this book, you will find boxed features called ***How Do We Know?*** They will help you understand how scientists use the methods of science to know what the universe is like.

Expect to Be Astonished

One reason astronomy is exciting is that astronomers discover new things every day. Astronomers expect to be astonished. You can share in the excitement because we have worked hard to include the newest images, the newest discoveries, and the newest insights that will take you, in an introductory course, to the frontier of human knowledge. Huge telescopes in space and on remote mountaintops provide a daily dose of excitement that goes far beyond sensationalism. These new discoveries in astronomy are exciting because they are about us. They tell us more and more about what we are.

As you read this book, notice that it is not organized as lists of facts for you to memorize. That could make even astronomy boring. Rather this book is organized to show you how scientists use evidence and theory to create logical arguments that show how nature works. Look at the list of special features that follows this note. Those features were carefully designed to help you understand

astronomy as evidence and theory. Once you see science as evidence and logical arguments, you hold the key to the universe.

Do Not Be Humble

As teachers, our quest is simple. We want you to understand your place in the universe—not just your location in space but your location in the unfolding history of the physical universe. Not only do we want you to know where you are and what you are in the universe; we also want you to understand how scientists know. By the end of this book, we want you to know that the universe is very big but that it is described by a small set of rules and that we humans have found a way to figure out the rules—a method called science.

To appreciate your role in this beautiful universe, you must learn more than just the facts of astronomy. You must understand what we are and how we know. Every page of this book reflects that ideal.

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Key Content and Pedagogical Changes to the Eleventh Edition

- Every chapter has been reviewed and updated with the latest discoveries and images, such as photos of colliding galaxies and planets orbiting distant stars. You will read about methane lakes on Saturn's moon Titan and the newest understanding of bursts of gamma rays detected coming from the most distant galaxies.
- Some chapters have been reorganized and rewritten to better present their topics. Chapter 10, "The Interstellar Medium," and Chapter 11, "The Formation and Structure of Stars," are completely reorganized to better explain the gas and dust between the stars and how stars form from that material. Chapter 17, "Active Galaxies and Supermassive Black Holes," is newly redesigned to include the latest understanding of these peculiar objects.
- Chapter 4, "The Origin of Modern Astronomy," has been reorganized to better tell the story of the development of scientific thought at the end of the Renaissance. Chapter 15, "The Milky Way Galaxy," has been reorganized to better convey the roles each part of the galaxy have played in its history and evolution. Chapter 19, "Astrobiology" Life on Other Worlds," has a new subsection on "extremophiles," life that thrives on Earth in extreme environments.
- Guideposts for all of the chapters have been rewritten and shortened to open each chapter with a short list of questions that will help you focus your reading on the main objectives of the chapter.
- Throughout the book, the newest images have been included to keep you up to date with the rapid advances in modern astronomy.
- **Focus on Fundamentals** will help you understand five concepts from physics that are critical to understanding modern astronomy.
- **Guideposts** on the opening page of each chapter help you see the organization of the book by focusing on a small number of questions to be answered as you read the chapter.
- **Scientific Arguments** at the end of many text sections are carefully designed questions to help you review and synthesize concepts from the section. A short answer follows to show how scientists construct scientific arguments from observations, evidence, theories, and natural laws that lead to a conclusion. A further question then gives you a chance to construct your own scientific argument on a related issue.
- **End-of-Chapter Review Questions** are designed to help you review and test your understanding of the material.
- **End-of-Chapter Discussion Questions** go beyond the text and invite you to think critically and creatively about scientific questions. You can think about these questions yourself or discuss them in class.
- **Virtual Astronomy Laboratories.** These online labs give you an exciting, interactive way to learn, putting some of astronomy's most useful instruments into your hands—precise telescope controls to measure angular size, a photometer to measure light intensity, and a spectrograph to measure Doppler-shifted spectral lines.
- **TheSky Student Edition CD-ROM** turns a personal computer into a powerful personal planetarium. Loaded with data on 118,000 stars and 13,000 deep-sky objects with images, it allows you to view the universe at any point in time from 4000 years ago to 8000 years in the future, to see the sky in motion, to view constellations, to print star charts, and much more.

Special Features

- **What Are We?** essays are placed at the end of each chapter to help you understand your own role in the astronomy you have just learned.
- **How Do We Know?** commentaries appear in every chapter and will help you see how science works. They will point out where scientists use statistical evidence, why they think with analogies, and how they build confidence in theories.
- **Special two-page art spreads** provide an opportunity for you to create your own understanding and share in the satisfaction that scientists feel as they uncover the secrets of nature.
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We would especially like to thank the reviewers whose careful analysis and thoughtful suggestions have been invaluable in completing this new edition.

Many observatories, research institutes, laboratories, and individual astronomers have supplied figures and diagrams for this edition. They are listed next to each figure, and we would like to thank them specifically for their generosity.

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Mike Seeds
Dana Backman

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1

Here and Now



Visual wavelength image

Guidepost

As you study astronomy, you will learn about yourself. You are a planet walker, and this chapter will give you a preview of what that means. The planet you live on whirls around a star that drifts through a universe filled with other stars and galaxies. You owe it to yourself to know where you are in the universe because that is the first step to knowing what you are.

In this chapter, you will meet three essential questions about astronomy:

— **Where are you in the universe?**

— **How does human history fit into the time scale of the universe?**

— **Why should you study astronomy?**

As you study astronomy, you will see how science gives you a way to know how nature works. In this chapter, you can begin thinking about science in a general way. Later chapters will give you more specific insights into how scientists work and think and know about nature.

This chapter is a jumping-off place for your exploration of deep space and deep time. The next chapter continues your journey by looking at the night sky as seen from Earth.

These clouds of gas are so far away that their light takes 7200 years to reach Earth. They are a small part of a larger cloud that has formed a cluster of stars. More stars are probably forming in the darkest, densest parts of the cloud. (NASA, ESA, and The Hubble Heritage Team, STScI/AURA)

*The longest journey begins
with a single step.*

— LAO TSE

1-1 Where Are You?

TO FIND YOUR PLACE among the stars, you can take a cosmic zoom, a ride out through the universe to preview the kinds of objects you are about to study.

You can begin with something familiar. ■ Figure 1-1 shows a region about 50 feet across occupied by a human being, a sidewalk, and a few trees—all objects whose size you can understand. Each successive picture in this cosmic zoom will show you a region of the universe that is 100 times wider than the preceding picture. That is, each step will widen your **field of view**, the region you can see in the image, by a factor of 100.

Widening your field of view by a factor of 100 allows you to see an area 1 mile in diameter (■ Figure 1-2). People, trees, and sidewalks have become too small to see, but now you see a college campus and surrounding streets and houses. The dimensions of houses and streets are familiar. This is still the world you know.

Before leaving this familiar territory, you should make a change in the units you use to measure sizes. All scientists, including astronomers, use the metric system of units because it is well understood worldwide and, more important, because it simplifies



■ **Figure 1-1**

Michael A. Seeds



■ **Figure 1-2**

This box ■ represents the relative size of the previous frame. (USGS)

calculations. If you are not already familiar with the metric system, or if you need a review, study Appendix A before reading on.

The photo in Figure 1-2 is 1 mile across, which equals about 1.6 kilometers. You can see that a kilometer (abbreviated km) is a bit under two-thirds of a mile—a short walk across a neighborhood. But when you expand your field of view by a factor of 100, the neighborhood you saw in the previous photo vanishes (■ Figure 1-3). Now your field of view is 160 km wide, and you see cities and towns as patches of gray. Wilmington, Delaware, is visible at the lower right. At this scale, you can see some of the natural features of Earth's surface. The Allegheny Mountains of southern Pennsylvania cross the image in the upper left, and the Susquehanna River flows southeast into Chesapeake Bay. What look like white bumps are a few puffs of clouds.

Figure 1-3 is an infrared photograph in which healthy green leaves and crops show up as red. Human eyes are sensitive to only a narrow range of colors. As you explore the universe, you will learn to use a wide range of other “colors,” from X-rays to radio waves, to reveal sights invisible to unaided human eyes. You will learn much more about infrared, X-rays, and radio energy in later chapters.

At the next step in your journey, you can see your entire planet, which is nearly 13,000 km in diameter (■ Figure 1-4). At any particular moment, half of Earth's surface is exposed to sunlight, and half is in darkness. As Earth rotates on its axis, it carries you through sunlight and then through darkness, producing the cycle of day and night. The blurriness you see at the extreme right of the photo is the boundary between day and night—the sunset line. This is a good example of how a photo can give you



■ **Figure 1-3**

NASA

visual clues to understanding a concept. Special questions called “Learning to Look” at the end of each chapter give you a chance to use your own imagination to connect images with theories about astronomical objects.



■ **Figure 1-4**

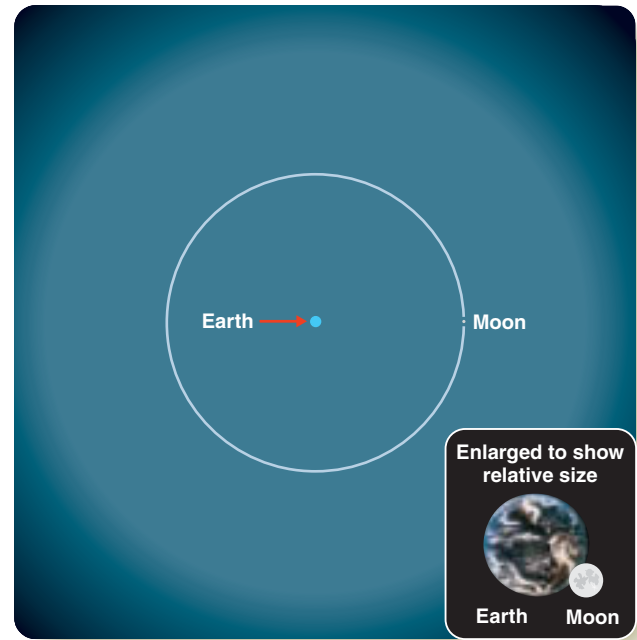
NASA

Enlarge your field of view by a factor of 100, and you see a region 1,600,000 km wide (■ Figure 1-5). Earth is the small blue dot in the center, and the moon, whose diameter is only one-fourth that of Earth, is an even smaller dot along its orbit 380,000 km away.

These numbers are so large that it is inconvenient to write them out. Astronomy is sometimes known as the science of big numbers, and soon you will be using numbers much larger than these to discuss the universe. Rather than writing out these numbers as in the previous paragraph, it is more convenient to write them in **scientific notation**. This is nothing more than a simple way to write very big or very small numbers without using lots of zeros. In scientific notation, 380,000 becomes 3.8×10^5 . If you are not familiar with scientific notation, read the section on powers of 10 notation in Appendix A. The universe is too big to discuss without using scientific notation.

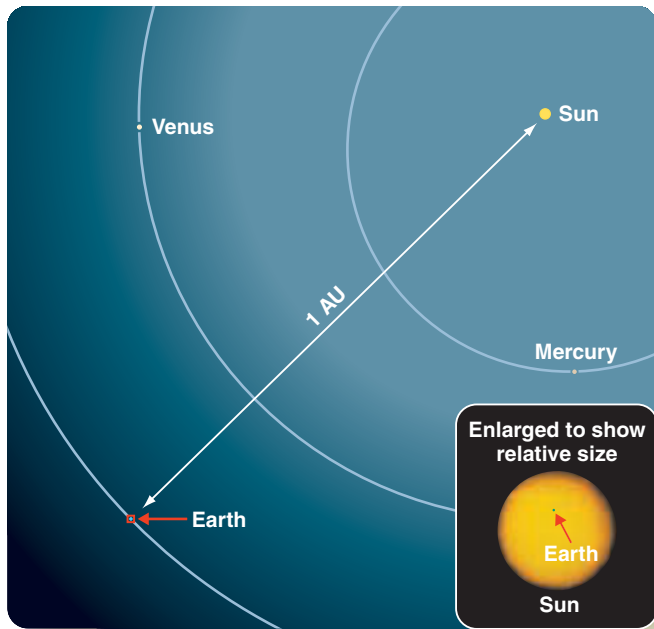
When you once again enlarge your field of view by a factor of 100, Earth, the moon, and the moon’s orbit all lie in the small red box at lower left of ■ Figure 1-6. Now you can see the sun and two other planets that are part of our solar system. Our **solar system** consists of the sun, its family of planets, and some smaller bodies, such as moons and comets.

Earth, Venus, and Mercury are **planets**, small, spherical, nonluminous bodies that orbit a star and shine by reflected light. Venus is about the size of Earth, and Mercury is just over a third of Earth’s diameter. On the diagram, they are both too small to be seen as anything but tiny dots. The sun is a **star**, a self-luminous



■ **Figure 1-5**

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■ **Figure 1-6**

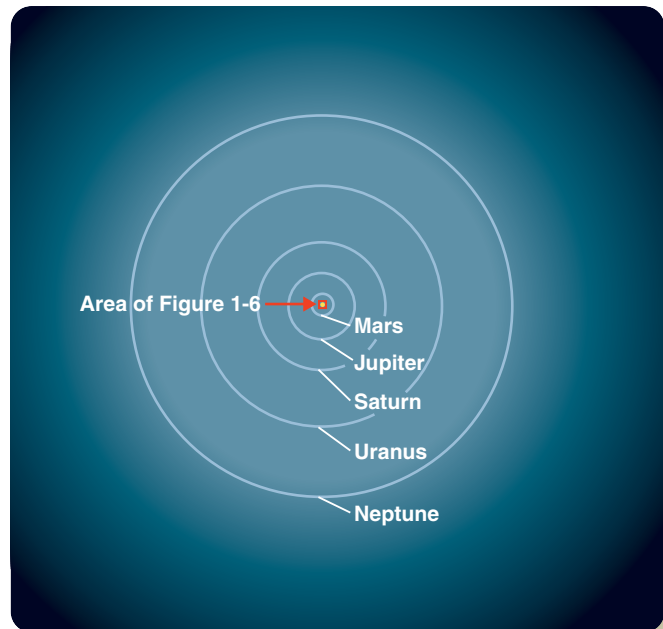
NOAO

ball of hot gas that generates its own energy. Even though the sun is 109 times larger in diameter than Earth (inset), it too is nothing more than a dot in this diagram.

This diagram represents an area with a diameter of 1.6×10^8 km. One way astronomers simplify calculations using large numbers is to define larger units of measurement. For example, the average distance from Earth to the sun is a unit of distance called the **astronomical unit (AU)**, which is equal to 1.5×10^8 km. Using that, you can express the average distance from Venus to the sun as about 0.72 AU and the average distance from Mercury to the sun as about 0.39 AU.

These distances are averages because the orbits of the planets are not perfect circles. This is particularly apparent in the case of Mercury. Its orbit carries it as close to the sun as 0.307 AU and as far away as 0.467 AU. You can see the variation in the distance from Mercury to the sun in Figure 1-6. Earth's orbit is more circular, and its distance from the sun varies by only a few percent.

Enlarge your field of view again, and you can see the entire solar system (■ Figure 1-7). The sun, Mercury, Venus, and Earth lie so close together that you cannot see them separately at this scale, and they are lost in the red square at the center of this diagram. You can see only the brighter, more widely separated objects such as Mars, the next planet outward. Mars is only 1.5 AU from the sun, but Jupiter, Saturn, Uranus, and Neptune are farther from the sun and so are easier to place in this diagram. They are cold worlds far from the sun's warmth. Light from the sun



■ **Figure 1-7**

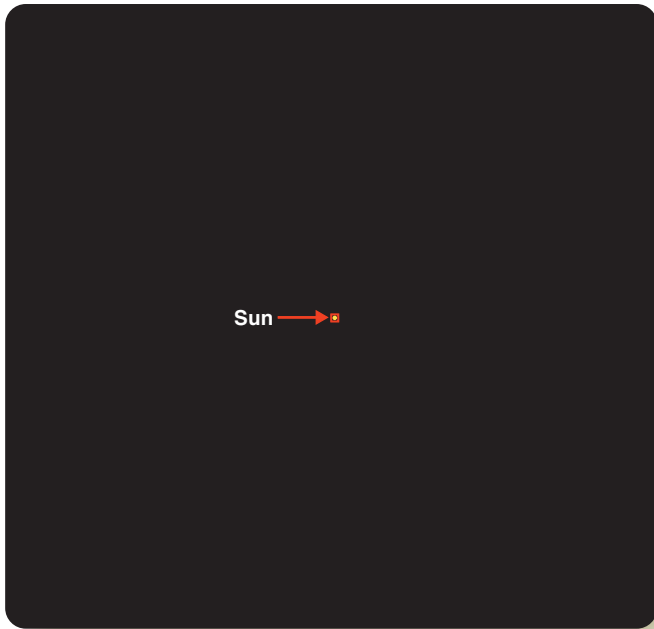
reaches Earth in only 8 minutes, but it takes over 4 hours to reach Neptune.

You can remember the order of the planets from the sun outward by remembering a simple sentence: *My Very Educated Mother Just Served Us Noodles*. The first letter of each word reminds you of a planet: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune.

When you again enlarge your field of view by a factor of 100, the solar system vanishes (■ Figure 1-8). The sun is only a point of light, and all the planets and their orbits are now crowded into the small red square at the center. The planets are too small and too faint to be visible so near the brilliance of the sun.

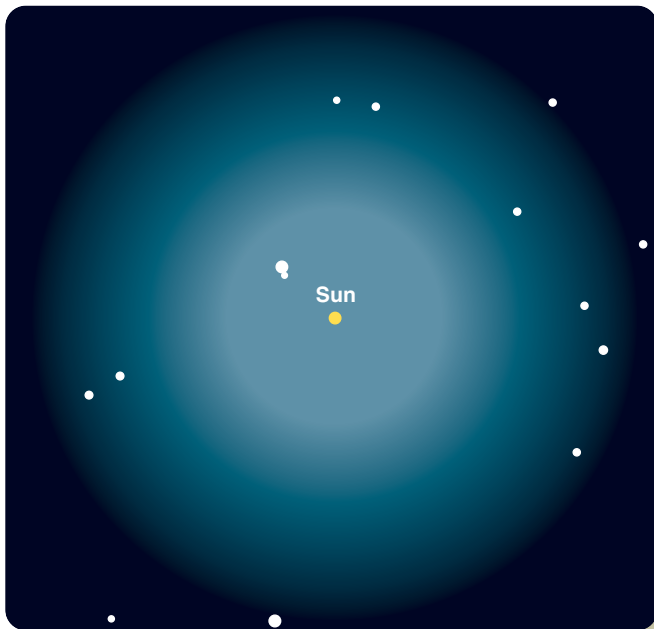
Nor are any stars visible except for the sun. The sun is a fairly typical star, and it seems to be located in a fairly average neighborhood in the universe. Although there are many billions of stars like the sun, none are close enough to be visible in this diagram, which shows a region only 11,000 AU in diameter. Stars in the sun's neighborhood are typically separated by distances about 30 times larger than that.

In ■ Figure 1-9, your field of view has expanded to a diameter of a bit over 1 million AU. The sun is at the center, and at this scale you can see a few of the nearest stars. These stars are so distant that it is not convenient to give their distances in astronomical units. To express distances so large, astronomers define a new unit of distance, the light-year. One **light-year (ly)** is the distance that light travels in one year, roughly 10^{13} km or 63,000 AU. It is a **Common Misconception** that a light-



■ **Figure 1-8**

year is a unit of time, and you can sometimes hear the term misused in science fiction movies and TV shows. The next time you hear someone say, “It will take me light-years to finish my history paper,” you could tell the person that a light-year is a distance, not a time. The diameter of your field of view in Figure 1-9 is 17 ly.



■ **Figure 1-9**

Another **Common Misconception** is that stars look like disks when seen through a telescope. Although stars are roughly the same size as the sun, they are so far away that astronomers cannot see them as anything but points of light. Even the closest star to the sun—Alpha Centauri, only 4.2 ly from Earth—looks like a point of light through even the biggest telescopes on Earth. Furthermore, planets that circle other stars are much too small, too faint, and too close to the glare of their star to be easily visible. Astronomers have used indirect methods to detect over 300 planets orbiting other stars, but very few have been photographed directly.

Figure 1-9 follows the astronomical custom of making the sizes of the dots represent not the sizes of the stars but their brightness. This is how star images are recorded on photographs. Bright stars make larger spots on a photograph than faint stars, so the size of a star image in a photograph tells you not how big the star is but only how bright it looks.

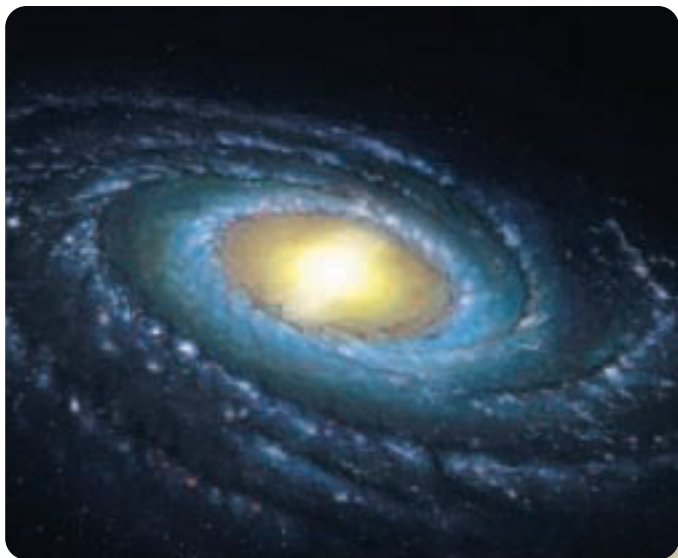
In ■ Figure 1-10, you expand your field of view by another factor of 100, and the sun and its neighboring stars vanish into the background of thousands of other stars. The field of view is now 1700 ly in diameter. Of course, no one has ever journeyed thousands of light-years from Earth to look back and photograph the solar neighborhood, so this is a representative photograph of the sky. The sun is a relatively faint star that would not be easily located in a photo at this scale.

If you again expand your field of view by a factor of 100, you see our galaxy, a disk of stars about 80,000 ly in diameter (■ Figure 1-11). A **galaxy** is a great cloud of stars, gas, and dust



■ **Figure 1-10**

NOAO



■ **Figure 1-11**

© Mark Garlick/space-art.com

held together by the combined gravity of all of its matter. Galaxies range from 1500 to over 300,000 ly in diameter, and some contain over 100 billion stars. In the night sky, you can see our galaxy as a great, cloudy wheel of stars ringing the sky. This band of stars is known as the **Milky Way**, and our galaxy is called the **Milky Way Galaxy**.

How does anyone know what our galaxy looks like if no one can leave it and look back? Astronomers use evidence to guide their explanations as they imagine what the Milky Way looks like. Artists can then use those scientific descriptions to create a painting. Many images in this book are artists' renderings of objects and events that are too big or too dim to see clearly, emit energy your eyes cannot detect, or happen too slowly or too rapidly for humans to sense. These images are not just guesses; they are scientifically based illustrations guided by the best information astronomers can gather. As you explore, notice how astronomers use the methods of science to imagine, understand, and depict cosmic events.

The artist's conception of the Milky Way reproduced in Figure 1-11 shows that our galaxy, like many others, has graceful **spiral arms** winding outward through its disk. In a later chapter, you will learn that the spiral arms are places where stars are formed from clouds of gas and dust. Our own sun was born in one of these spiral arms; and, if you could see the sun in this picture, it would be in the disk of the galaxy about two-thirds of the way out from the center.

Ours is a fairly large galaxy. Only a century ago astronomers thought it was the entire universe—an island cloud of stars in an otherwise empty vastness. Now they know that our galaxy is not unique; it is only one of many billions of galaxies scattered throughout the universe.

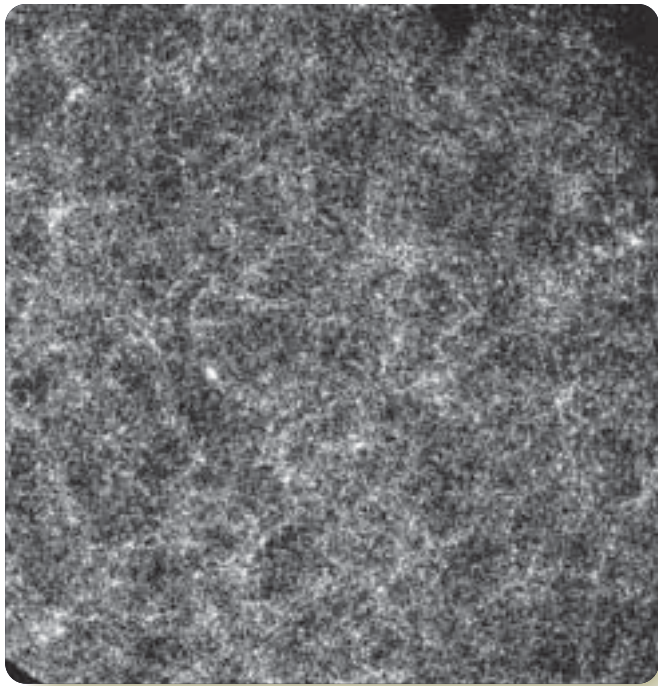


■ **Figure 1-12**

You can see a few of these other galaxies when you expand your field of view by another factor of 100 (■ Figure 1-12). Our galaxy appears as a tiny luminous speck surrounded by other specks in a region 17 million light-years in diameter. Each speck represents a galaxy. Notice that our galaxy is part of a cluster of a few dozen galaxies. Galaxies are commonly grouped together in such clusters. Some galaxies have beautiful spiral patterns like our own galaxy, but others do not. Some are strangely distorted. In a later chapter, you will learn what produces these differences among the galaxies.

Now is a chance for you to correct another **Common Misconception**. People often say “galaxy” when they mean “solar system,” and they sometimes confuse both terms with “universe.” Your cosmic zoom has shown you the difference. The solar system is the sun and its planets. Our galaxy contains our solar system plus billions of other stars and whatever planets orbit around them, in other words, billions of planetary systems. The universe includes everything: all of the galaxies, stars, and planets, including our own galaxy and a very small part of it, our solar system.

If you expand your field of view one more time, you can see that clusters of galaxies are connected in a vast network (■ Figure 1-13). Clusters are grouped into superclusters—clusters of clusters—and the superclusters are linked to form long filaments and walls outlining nearly empty voids. These filaments and walls appear to be the largest structures in the universe. Were you to expand your field of view another time, you would probably see a uniform fog of filaments and walls. When you puzzle over the origin of these structures, you are at the frontier of human knowledge.



■ **Figure 1-13**

(Based on data from M. Seldner, B. L. Siebers, E. J. Groth, and P. J. E. Peebles, *Astronomical Journal* 82 [1977].)

1-2 When Is Now?

NOW THAT YOU HAVE AN IDEA where you are in space, you need to know where you are in time. The stars shined for billions of years before the first human looked up and wondered what they were. To get a sense of your place in time, all you need is a long red ribbon.

Imagine stretching a ribbon from goal line to goal line down the center of a football field, as shown on the inside front cover of this book. Imagine that one end of the ribbon is *today* and that the other end represents the beginning of the universe—the moment of beginning that astronomers call the *big bang*. In a later chapter, “Modern Cosmology,” you will learn all about the big bang and see evidence that the universe is about 14 billion years old. Your long red ribbon represents 14 billion years, the entire history of the universe.

Imagine beginning at the goal line labeled *Big Bang* and replaying the entire history of the universe as you walk along your ribbon toward the goal line labeled *Today*. Observations tell astronomers that the big bang filled the entire universe with hot, glowing gas, but as the gas cooled and dimmed the universe went dark. All that happened along the first half inch of the ribbon. There was no light for the first 400 million years, until gravity was able to pull some of the gas together to form the first stars. That seems like a lot of years, but if you stick a little flag beside

the ribbon to mark the birth of the first stars, it would be not quite 3 yards from the goal line where the universe began.

You have to walk only about 5 yards along the ribbon before galaxies formed in large numbers. Our home galaxy would be one of those taking shape. By the time you cross the 50-yard line, the universe is full of galaxies, but the sun and Earth have not formed yet. You need to walk past the 50-yard line down to the 35-yard line before you can finally stick a flag beside the ribbon to mark the formation of the sun and planets—our solar system.

You can carry your flags a few yards farther to the 29-yard line to mark the appearance of the first life on Earth—microscopic creatures in the oceans—and you have to walk all the way to the 3-yard line before you can mark the emergence of life on land. Your dinosaur flag goes just inside the 2-yard line. Dinosaurs go extinct as you pass the one-half-yard line.

What about people? You can put a little flag for the first humanlike creatures only about an inch—four million years—from the goal line labeled *Today*. Civilization, the building of cities, began about 10,000 years ago, so you have to try to fit that flag in only 0.0026 inch from the goal line. That’s half the thickness of a sheet of paper. Compare the history of human civilization with the history of the universe. Every war you have ever heard of, every person whose name is recorded, every structure ever built from Stonehenge to the building you are in right now fits into that 0.0026 inch.

Humanity is very new to the universe. Our civilization on Earth has existed for only a flicker of an eyeblink in the history of the universe. As you will discover in the chapters that follow, only in the last hundred years or so have astronomers begun to understand where we are in space and in time.

1-3 Why Study Astronomy?

YOUR EXPLORATION OF THE UNIVERSE will help you answer two fundamental questions:

What are we?
How do we know?

The question, “What are we?” is the first organizing theme of this book. Astronomy is important to you because it will tell you what you are. Notice that the question is not “*Who* are we?” If you want to know who we are, you may want to talk to a sociologist, theologian, paleontologist, artist, or poet. “*What* are we?” is a fundamentally different question.

As you study astronomy, you will learn how you fit into the history of the universe. You will learn that the atoms in your body had their first birthday in the big bang when the universe began. Those atoms have been cooked and remade inside generations of stars, and now, after billions of years, they are inside you. Where will they be in another billion years? This is a story

The So-Called Scientific Method

How do scientists learn about nature? You have probably heard of the scientific method as the process by which scientists form hypotheses and test them against evidence gathered by experiment or observation. Scientists use the scientific method all the time, and it is critically important, but they rarely think of it at all, and they certainly don't think of it as a numbered list of steps. It is such an ingrained way of thinking and understanding nature that it is almost invisible to the people who use it most.

Scientists try to form hypotheses that explain how nature works. If a hypothesis is contradicted by evidence from experiments or observations, it must be revised or discarded. If a hypothesis is confirmed, it must be tested further. In that very general way, the scientific method is a way of testing and refining ideas to better describe how nature works.

For example, Gregor Mendel (1822–1884) was an Austrian abbot who liked plants. He formed a hypothesis that offspring usually inherit traits from their parents not as a

smooth blend, as most scientists of the time believed, but in discrete units according to strict mathematical rules. Mendel cultivated and tested over 28,000 pea plants, noting which produced smooth peas and which produced wrinkled peas and how that trait was inherited by successive generations. His study of pea plants confirmed his hypothesis and allowed the development of a series of laws of inheritance. Although the importance of his work was not recognized in his lifetime, Mendel is now called the “father of modern genetics.”

The scientific method is not a simple, mechanical way of grinding facts into understanding. It is, in fact, a combination of many ways of analyzing information, finding relationships, and creating new ideas. A scientist needs insight and ingenuity to form and test a good hypothesis. Scientists use the scientific method almost automatically, forming, testing, revising, and discarding hypotheses almost minute by minute as they discuss a new idea. Sometimes, however,



Whether peas are wrinkled or smooth is an inherited trait (Inspirestock/jupiterimages).

a scientist will spend years studying a single promising hypothesis. The so-called scientific method is a way of thinking and a way of knowing about nature. The “How Do We Know?” essays in the chapters that follow will introduce you to some of those methods.

everyone should know, and astronomy is the only course on campus that can tell you that story.

Every chapter in this book ends with a short segment titled “What Are We?” This summary shows how the astronomy in the chapter relates to your role in the story of the universe.

The question, “How do we know?” is the second organizing theme of this book. It is a question you should ask yourself whenever you encounter statements made by so-called experts in any field. Should you swallow a diet supplement recommended by a TV star? Should you vote for a candidate who warns of a climate crisis? To understand the world around you and to make wise decisions for yourself, for your family, and for your nation, you need to understand how science works.

You can use astronomy as a case study in science. In every chapter of this book, you will find short essays titled “How Do We Know?” They are designed to help you think not about *what* is known but about *how* it is known. To do that, they will explain different aspects of scientific reasoning and in that way help you understand how scientists know about the natural world.

Over the last four centuries, scientists have developed a way to understand nature that has been called the **scientific method** (**How Do We Know? 1-1**). You will see this process applied over and over as you read about exploding stars, colliding galaxies, and alien planets. The universe is very big, but it is described by a small set of rules, and we humans have found a way to figure out the rules—a method called *science*.

What Are We? Part of the Story

Astronomy will give you perspective on what it means to be here on Earth. This chapter has helped you locate yourself in space and time. Once you realize how vast our universe is, Earth seems quite small. People on the other side of the world seem like neighbors. And, in the entire history of the universe, the human story is only the

blink of an eye. This may seem humbling at first, but you can be proud of how much we humans have understood in such a short time.

Not only does astronomy locate you in space and time, it places you in the physical processes that govern the universe. Gravity and atoms work together to make stars,

light the universe, generate energy, and create the chemical elements in your body. The chapters that follow will show how you fit into that cosmic process.

Although you are very small and your kind have existed in the universe for only a short time, you are an important part of something very large and very beautiful.

Study and Review

Summary

- ▶ You surveyed the universe by taking a cosmic zoom in which each **field of view (p. 2)** was 100 times wider than the previous field of view.
- ▶ Astronomers use the metric system because it simplifies calculations and use **scientific notation (p. 3)** for very large or very small numbers.
- ▶ You live on a **planet (p. 3)**, Earth, which orbits our **star (p. 3)**, the sun, once a year. As Earth rotates once a day, you see the sun rise and set.
- ▶ The moon is only one-fourth the diameter of Earth, but the sun is 109 times larger in diameter than Earth—a typical size for a star.
- ▶ The **solar system (p. 3)** includes the sun at the center, all of the planets that orbit around it—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune—plus the moons of the planets, plus other objects bound to the sun by its gravity.
- ▶ The **astronomical unit (AU) (p. 4)** is the average distance from Earth to the sun. Mars, for example, orbits 1.5 AU from the sun. The **light-year (ly) (p. 4)** is the distance light can travel in one year. The nearest star is 4.2 ly from the sun.
- ▶ Many stars seem to have planets, but such small, distant worlds are difficult to detect. Only a few hundred have been found so far, but planets seem to be common, so you can probably trust that there are lots of planets in the universe, including some like Earth.
- ▶ The **Milky Way (p. 6)**, the hazy band of light that encircles the sky, is the **Milky Way Galaxy (p. 6)** seen from inside. The sun is just one out of the billions of stars that fill the Milky Way Galaxy.
- ▶ **Galaxies (p. 5)** contain many billions of stars. Our galaxy is about 80,000 ly in diameter and contains over 100 billion stars.
- ▶ Some galaxies, including our own, have graceful **spiral arms (p. 6)** bright with stars, but some galaxies are plain clouds of stars.
- ▶ Our galaxy is just one of billions of galaxies that fill the universe in great clusters, clouds, filaments, and walls—the largest structures in the universe.
- ▶ The universe began about 14 billion years ago in an event called the big bang, which filled the universe with hot gas.

- ▶ The hot gas cooled, the first galaxies began to form, and stars began to shine only about 400 million years after the big bang.
- ▶ The sun and planets of our solar system formed about 4.6 billion years ago.
- ▶ Life began in Earth's oceans soon after Earth formed but did not emerge onto land until only 400 million years ago. Dinosaurs evolved not long ago and went extinct only 65 million years ago.
- ▶ Humanlike creatures developed on Earth only about 4 million years ago, and human civilizations developed only about 10,000 years ago.
- ▶ Although astronomy seems to be about stars and planets, it describes the universe in which you live, so it is really about you. Astronomy helps you answer the question, "What are we?"
- ▶ As you study astronomy, you should ask "How do we know?" and that will help you understand how science gives us a way to understand nature.
- ▶ In its simplest outline, science follows the **scientific method (p. 8)**, in which scientists expect statements to be supported by evidence compared with hypotheses. In fact, science is a complex and powerful way to think about nature.

Review Questions

1. What is the largest dimension of which you have personal knowledge? Have you run a mile? Hiked 10 miles? Run a marathon?
2. What is the difference between our solar system, our galaxy, and the universe?
3. Why are light-years more convenient than miles, kilometers, or astronomical units for measuring certain distances?
4. Why is it difficult to detect planets orbiting other stars?
5. What does the size of the star image in a photograph tell you?
6. What is the difference between the Milky Way and the Milky Way Galaxy?
7. What are the largest known structures in the universe?
8. How does astronomy help answer the question, "What are we?"
9. **How Do We Know?** How does the scientific method give scientists a way to know about nature?

Discussion Questions

1. Do you think you have a right to know the astronomy described in this chapter? Do you think you have a duty to know it? Can you think of ways this knowledge helps you enjoy a richer life and be a better citizen?
2. How is a statement in a political campaign speech different from a statement in a scientific discussion? Find examples in newspapers, magazines, and this book.

Problems

1. The diameter of Earth is 7928 miles. What is its diameter in inches? In yards? If the diameter of Earth is expressed as 12,756 km, what is its diameter in meters? In centimeters? Give your answers in scientific notation.
2. If a mile equals 1.609 km and the moon is 2160 miles in diameter, what is its diameter in kilometers?
3. One astronomical unit is about 1.5×10^8 km. Explain why this is the same as 150×10^6 km.
4. Venus orbits 0.72 AU from the sun. What is that distance in kilometers?
5. Light from the sun takes 8 minutes to reach Earth. How long does it take to reach Mars?
6. The sun is almost 400 times farther from Earth than is the moon. How long does light from the moon take to reach Earth?
7. If the speed of light is 3×10^5 km/s, how many kilometers are in a light-year? How many meters?
8. How long does it take light to cross the diameter of our Milky Way Galaxy?
9. The nearest galaxy to our own is about 2 million light-years away. How many meters is that?
10. How many galaxies like our own would it take, laid edge to edge, to reach the nearest galaxy? (*Hint:* See Problem 9.)

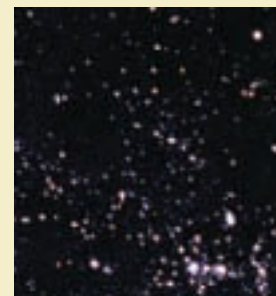
Learning to Look

1. In Figure 1-4, the division between daylight and darkness is at the right on the globe of Earth. How do you know this is the sunset line and not the sunrise line?
2. Look at Figure 1-6. How can you tell that Mercury does not follow a circular orbit?
3. Of the objects listed here, which would be contained inside the object shown in the photograph at the right? Which would contain the object in the photo?
stars
planets
galaxy clusters
filaments
spiral arms



Bill Schoening/NOAO/AURA/NSF

4. In the photograph shown here, which stars are brightest, and which are faintest? How can you tell? Why can't you tell which stars in this photograph are biggest or which have planets?



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2

The Sky



Guidepost

The previous chapter took you on a cosmic zoom through space and time. That quick preview only sets the stage for the drama to come. Now it is time to look closely at the sky and answer four essential questions:

— **How do astronomers refer to stars and compare their brightness?**

— **How does the sky appear to move as Earth rotates?**

— **What causes the seasons?**

— **How can astronomical cycles affect Earth's climate?**

As you study the sky and its motions, you will be learning to think of Earth as a planet rotating on its axis. The next chapter will introduce you to some of the most dramatic cycles in the sky.

The sky above mountain-top observatories far from city lights is the same sky you see from your window. The stars above you are other suns scattered through the universe.
(Kris Koenig/Coast Learning Systems)

*The Southern Cross I saw every night
abeam. The sun every morning came up
astern; every evening it went down ahead.
I wished for no other compass to guide me,
for these were true.*

— CAPTAIN JOSHUA SLOCUM
SAILING ALONE AROUND THE WORLD

THE NIGHT SKY is the rest of the universe as seen from our planet. When you look up at the stars, you are looking out through a layer of air only a little more than a hundred kilometers deep. Beyond that, space is nearly empty, and the stars are scattered light-years apart.

As you read this chapter, keep in mind that you live on a planet in the midst of these scattered stars. Because Earth turns on its axis once a day, the sky appears to revolve around you in a daily cycle. Not only does the sun rise in the eastern part of the sky and set in the western part, but so do the stars.

2-1 The Stars

ON A DARK NIGHT far from city lights, you can see a few thousand stars. The ancients organized what they saw by naming stars and groups of stars. Some of those names survive today.

Constellations

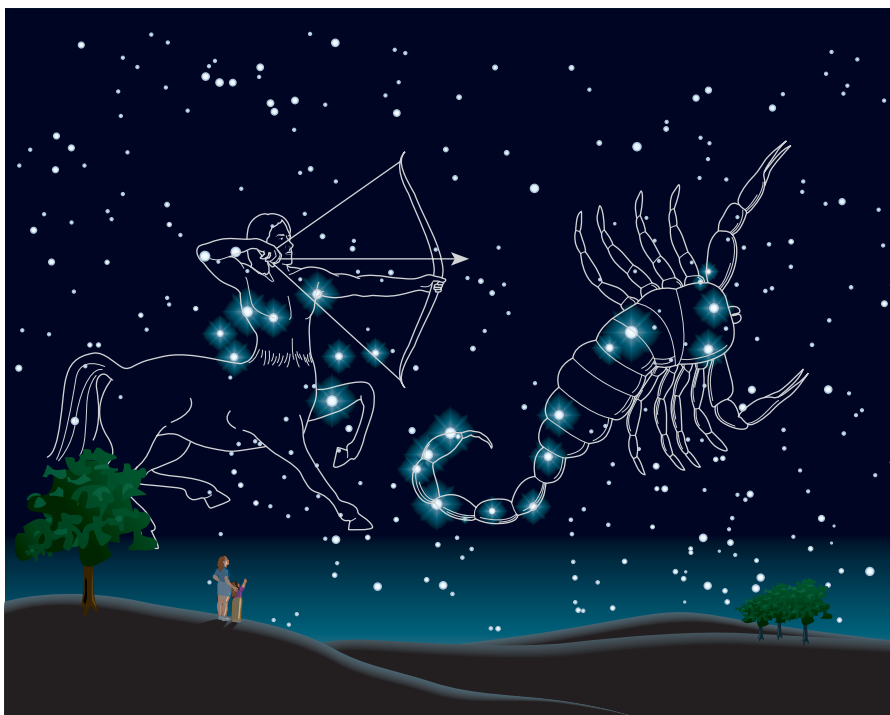
All around the world, ancient cultures celebrated heroes, gods, and mythical beasts by giving their names to groups of stars—**constellations** (■ Figure 2-1). You should not be surprised that the star patterns do not look like the creatures they represent any more than Columbus, Ohio, looks like Christopher Columbus. The constellations simply celebrate the most important mythical figures in each culture. The oldest constellations named by Western cultures originated in Assyria over 3000 years ago, and others were added by Babylonian and Greek astronomers during the classical age. Of these ancient constellations, 48 are still in use.

Different cultures grouped stars and named constellations differently. The constellation you know as Orion was known as Al Jabar, the giant, to the ancient Syrians, as the White Tiger to the Chinese, and as Prajapati in the Form of a Stag in India. The Pawnee Indians knew the constellation Scorpius as two

groupings. The long tail of the scorpion was the Snake, and the two bright stars at the tip of the scorpion's tail were the Two Swimming Ducks.

Many ancient cultures, including the Greeks, northern Asians, and Native Americans, associated the stars of the Big Dipper with a bear. The concept of the celestial bear may have crossed the land bridge into North America with the first Americans roughly 12,000 years ago. The names of some of the constellations you see in the sky may be among the oldest surviving traces of human culture.

To the ancients, a constellation was a loose grouping of stars. Many of the fainter stars were not included in any constellation, and the stars of the southern sky not visible to the ancient astronomers of northern latitudes were not grouped into constellations. Constellation boundaries, when they were defined at all, were only approximate (■ Figure 2-2a), so a star like Alpheratz could be thought of as part of Pegasus or part of Andromeda. To correct these gaps and ambiguities, astronomers have added 40 modern constellations, and in 1928 the International Astronomical Union established 88 official constellations with clearly defined boundaries (Figure 2-2b). Consequently, a constellation now represents not a group of stars but an area of the sky, and any star within the region belongs to one and only one constellation. Alpheratz belongs to Andromeda.



■ **Figure 2-1**

The constellations are an ancient heritage handed down for thousands of years as celebrations of great heroes and mythical creatures. Here Sagittarius and Scorpius hang above the southern horizon.

■ Figure 2-2

(a) In antiquity, constellation boundaries were poorly defined, as shown on this map by the curving dotted lines that separate Pegasus from Andromeda. (From Duncan Bradford, *Wonders of the Heavens*, Boston: John B. Russell, 1837.) (b) Modern constellation boundaries are precisely defined by international agreement.

In addition to the 88 official constellations, the sky contains a number of less formally defined groupings called **asterisms**. The Big Dipper, for example, is a well-known asterism that is part of the constellation Ursa Major (the Great Bear). Another asterism is the Great Square of Pegasus (Figure 2-2b), which includes three stars from Pegasus plus Alpheratz from Andromeda. The star charts at the end of this book will introduce you to the brighter constellations and asterisms.

Although constellations and asterisms are groups of stars that appear close together in the sky, it is important to remember that most are made up of stars that are not physically associated with one another. Some stars may be many times farther away than others and moving through space in different directions. The only thing they have in common is that they happen to lie in approximately the same direction from Earth (■ Figure 2-3).

The Names of the Stars

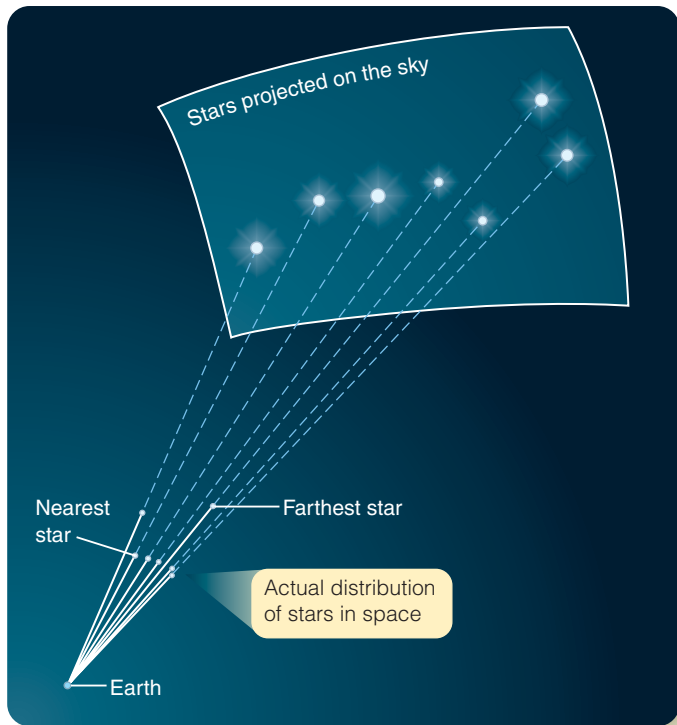
In addition to naming groups of stars, ancient astronomers gave individual names to the brightest individual stars. Modern astronomers still use many of those ancient names. Although the constellation names came from Greek translated into Latin—the language of science until the 19th century—most star names come from ancient Arabic, though much altered by the passing centuries. The name of Betelgeuse, the bright orange star in Orion, for example, comes from the Arabic *yad al jawza*, meaning “shoulder of Jawza [Orion].” Names such as Sirius (the Scorched One) and Aldebaran (the Follower of the Pleiades) are beautiful additions to the mythology of the sky.

Naming individual stars is not very helpful because you can see thousands of them. How many names could you remember? Also, a simple name gives you no clues to the location of the star

in the sky or to its brightness. A more useful way to identify stars is to assign letters to the bright stars in a constellation in approximate order of brightness. Astronomers use the Greek alphabet for this purpose. Thus, the brightest star in a constellation is usually designated alpha, the second brightest beta, and so on. Often the name of the Greek letter is spelled out, as in “alpha,” but sometimes the actual Greek letter is used, especially in charts. You will find the Greek alphabet in Appendix A. For many constellations, the letters follow the order of brightness, but some constellations, by tradition, mistake, or the personal preferences of early chart makers, are exceptions (■ Figure 2-4).

To identify a star by its Greek-letter designation, you would give the Greek letter followed by the possessive (genitive) form of the constellation name; for example, the brightest star in the constellation Canis Major is alpha Canis Majoris, which can also be written α Canis Majoris. This both identifies the star and the constellation and gives a clue to the relative brightness of the star. Compare this with the ancient name for this star, Sirius, which tells you nothing about location or brightness.





■ **Figure 2-3**

You see the Big Dipper in the sky because you are looking through a group of stars scattered through space at different distances from Earth. You see them as if they were projected on a screen, and they form the shape of the Dipper.

Favorite Stars

It is fun to know the names of the brighter stars, but they are more than points of light in the sky. They are glowing spheres of gas much like the sun, each with its unique characteristics. ■ Figure 2-5 identifies eight bright stars that you can adopt as Favorite Stars. As you study astronomy you will discover their peculiar personalities and enjoy finding them in the evening sky. You will learn, for example, that Betelgeuse is not just an orange point of light but is an aging, cool star over 800 times larger than the sun. As you learn more in later chapters, you may want to add more Favorite Stars to your list.

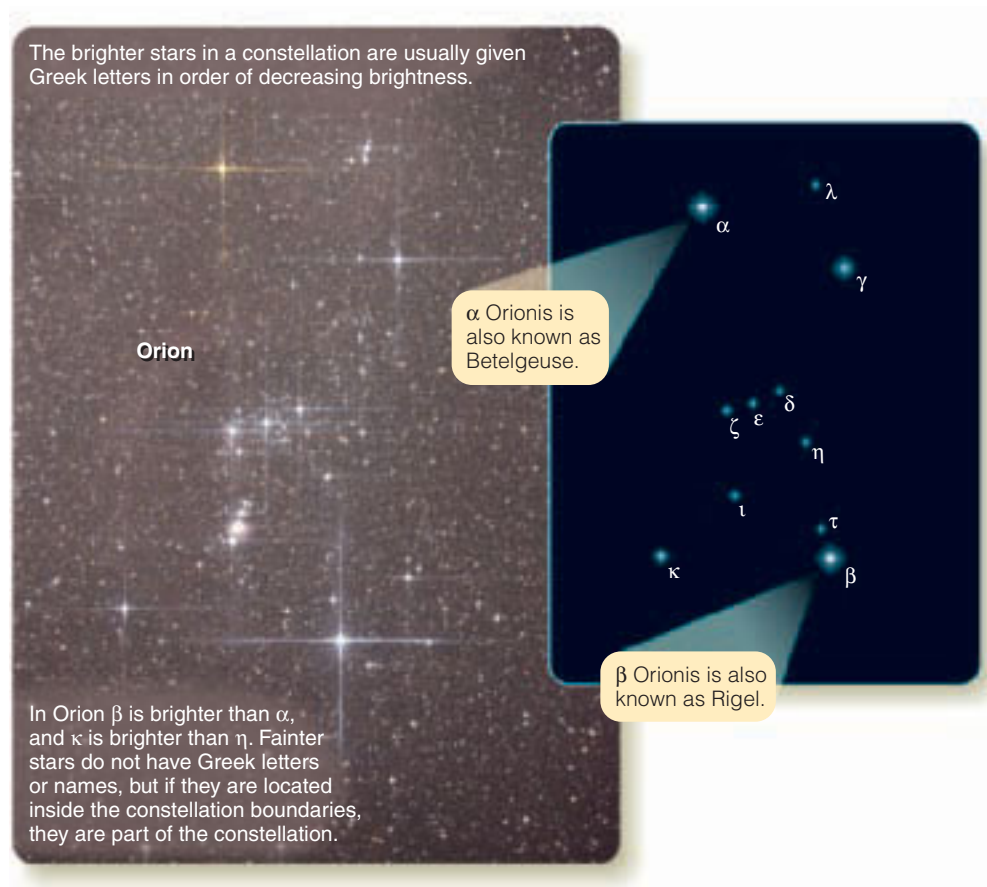
You can use the star charts at the end of this book to help you locate these Favorite Stars. You can see Polaris

year-round, but Sirius, Betelgeuse, Rigel, and Aldebaran are in the winter sky. Spica is a summer star, and Vega is visible evenings in later summer and fall. Alpha Centauri, only 4 ly away, is the nearest star to the sun, and you will have to travel as far south as southern Florida to glimpse it above the southern horizon.

The Brightness of Stars

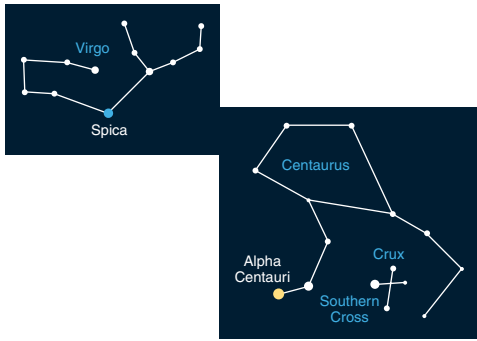
Besides naming individual stars, astronomers need a way to describe their brightness. Astronomers measure the brightness of stars using the **magnitude scale**, a system that first appeared in the writings of the ancient astronomer Claudius Ptolemy about AD 140. The system probably originated even earlier, and most astronomers attribute it to the Greek astronomer Hipparchus (about 190–120 BC). Hipparchus compiled the first known star catalog, and he may have used the magnitude system in that catalog. Almost 300 years later, Ptolemy used the magnitude system in his own catalog, and successive generations of astronomers have continued to use the system.

The ancient astronomers divided the stars into six classes. The brightest were called first-magnitude stars and those that

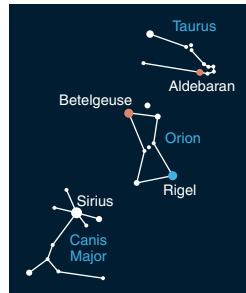
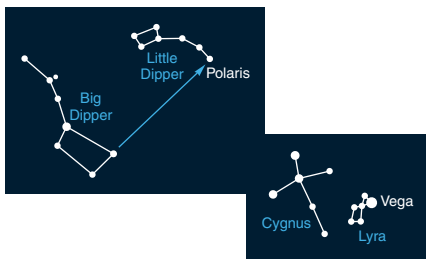


■ **Figure 2-4**

Stars in a constellation can be identified by Greek letters and by names derived from Arabic. The spikes on the star images in the photograph were produced by the optics in the camera. (William Hartmann)



Sirius	Brightest star in the sky	Winter
Betelgeuse	Bright red star in Orion	Winter
Rigel	Bright blue star in Orion	Winter
Aldebaran	Red eye of Taurus the Bull	Winter
Polaris	The North Star	Year round
Vega	Bright star overhead	Summer
Spica	Bright southern star	Summer
Alpha Centauri	Nearest star to the sun	Spring, far south



■ **Figure 2-5**

Favorite Stars: Locate these bright stars in the sky and learn why they are interesting.

were fainter, second-magnitude. The scale continued downward to sixth-magnitude stars, the faintest visible to the human eye. Thus, the larger the magnitude number, the fainter the star. This makes sense if you think of the bright stars as first-class stars and the faintest visible stars as sixth-class stars.

Ancient astronomers could only estimate magnitudes, but modern astronomers can measure the brightness of stars to high precision, so they have made adjustments to the scale of magnitudes. Instead of saying that the star known by the charming name Chort (Theta Leonis) is third magnitude, they can say its magnitude is 3.34. Accurate measurements show that some stars are actually brighter than magnitude 1.0. For example, Favorite Star Vega (alpha Lyrae) is so bright that its magnitude, 0.04, is

■ **Figure 2-6**

The scale of apparent visual magnitudes extends into negative numbers to represent the brightest objects and to positive numbers larger than 6 to represent objects fainter than the human eye can see.

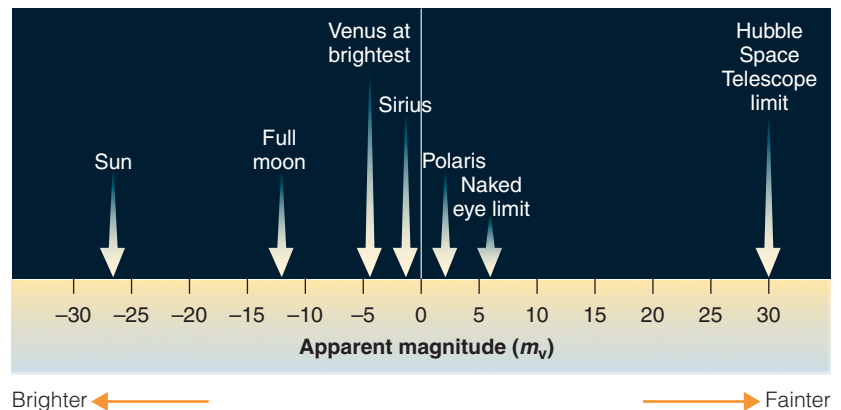
almost zero. A few are so bright the modern magnitude scale must extend into negative numbers (■ Figure 2-6). On this scale, our Favorite Star Sirius, the brightest star in the sky, has a magnitude of -1.47 . Modern astronomers have had to extend the faint end of the magnitude scale as well. The faintest stars you can see with your unaided eyes are about sixth magnitude, but if you use a telescope, you will see stars much fainter. Astronomers must use magnitude numbers larger than 6 to describe these faint stars.

These numbers are known as **apparent visual magnitudes** (m_v), and they describe how the stars look to human eyes observing from Earth. Although some stars emit large amounts of infrared or ultraviolet light, human eyes can't see those types of radiation, and they are not included in the apparent visual magnitude. The subscript "V" stands for "visual" and reminds you that only visible light is included. Apparent visual magnitude also does not take into account the distance to the stars. Very distant stars look fainter, and nearby stars look brighter. Apparent visual magnitude ignores the effect of distance and tells you only how bright the star looks as seen from Earth.

Magnitude and Intensity

Your interpretation of brightness is quite subjective, depending on both the physiology of human eyes and the psychology of perception. To be accurate you should refer to **flux**—a measure of the light energy from a star that hits one square meter in one second. Such measurements precisely define the intensity of starlight, and a simple relationship connects apparent visual magnitudes and intensity.

Astronomers use a simple formula to convert between magnitudes and intensities. If two stars have intensities I_A and I_B , then the ratio of their intensities is I_A/I_B . To make today's measurements agree with ancient catalogs, astronomers have defined the modern magnitude scale so that two stars that differ by five magnitudes have an intensity ratio of exactly 100. Then two stars that differ by one magnitude must have an intensity ratio that equals the fifth root of 100, $5\sqrt[5]{100}$, which equals about 2.512—that is, the light of one star must be 2.512 times more intense.



This allows you to compare the brightness of two stars. If they differ by two magnitudes, they will have an intensity ratio of 2.512×2.512 , or about 6.3. If they differ by three magnitudes, they will have an intensity ratio of $2.512 \times 2.512 \times 2.512$, which is 2.512^3 or about 6.3, and so on (■Table 2-1).

For example, suppose one star is third magnitude, and another star is ninth magnitude. What is the intensity ratio? In this case, the magnitude difference is six magnitudes, and the table shows the intensity ratio is 250. Therefore light from one star is 250 times more intense than light from the other star.

A table is convenient, but for more precision you can express the relationship as a simple formula. The intensity ratio I_A/I_B is equal to 2.512 raised to the power of the magnitude difference $m_B - m_A$:

$$\frac{I_A}{I_B} = (2.512)^{(m_B - m_A)}$$

If, for example, the magnitude difference is 6.32 magnitudes, then the intensity ratio must be $2.512^{6.32}$. A pocket calculator tells you the answer: 337. One of the stars is 337 times brighter than the other.

On the other hand, when you know the intensity ratio of two stars and want to find their magnitude difference, it is convenient to rearrange the formula above and write it as

$$m_B - m_A = 2.5 \log \left(\frac{I_A}{I_B} \right)$$

For example, the light from Sirius is 24.2 times more intense than light from Polaris. The magnitude difference is $2.5 \log(24.2)$. Your pocket calculator tells you the logarithm of 24.2 is 1.38, so the magnitude difference is 2.5×1.38 , which equals 3.4 magnitudes. Sirius is 3.4 magnitudes brighter than Polaris.

The modern magnitude system has some big advantages. It compresses a tremendous range of intensity into a small range of magnitudes, as you can see in Table 2-1. More important, it

allows modern astronomers to measure and report the brightness of stars to high precision while still making comparisons to observations of apparent visual magnitude that go back to the time of Hipparchus.

2-2 The Sky and Its Motion

THE SKY ABOVE seems to be a great blue dome in the daytime and a sparkling ceiling at night. It was this ceiling that the first astronomers observed long ago as they tried to understand the night sky.

The Celestial Sphere

Ancient astronomers believed the sky was a great sphere surrounding Earth with the stars stuck on the inside like thumbtacks in a ceiling. Modern astronomers know that the stars are scattered through space at different distances, but it is still convenient to think of the sky as a great starry sphere enclosing Earth.

The Concept Art Portfolio **The Sky Around You** on pages 18–19 takes you on an illustrated tour of the sky. Throughout this book, these two-page art spreads introduce new concepts and new terms through photos and diagrams. These concepts and new terms are not discussed elsewhere, so examine the art spreads carefully. Notice that **The Sky Around You** introduces you to three important principles and 16 new terms that will help you understand the sky:

- 1 The sky appears to rotate westward around Earth each day, but that is a consequence of the eastward rotation of Earth. That rotation produces day and night. Notice how reference points on the *celestial sphere* such as the *zenith*, *nadir*, *horizon*, *celestial equator*, and the *north celestial pole* and *south celestial pole* define the four directions, *north point*, *south point*, *east point*, and *west point*.
- 2 Astronomers measure *angular distance* across the sky as angles and express them as degrees, *arc minutes*, and *arc seconds*. The same units are used to measure the *angular diameter* of an object.
- 3 What you can see of the sky depends on where you are on Earth. If you lived in Australia, you would see many constellations and asterisms invisible from North America, but you would never see the Big Dipper. How many *circumpolar constellations* you see depends on where you are. Remember your Favorite Star Alpha Centauri? It is in the southern sky and isn't visible from most of the United States. You could just glimpse it above the southern horizon if you were in Miami, Florida, but you could see it easily from Australia.

Pay special attention to the new terms on pages 18–19. You need to know these terms to describe the sky and its motions, but don't fall into the trap of just memorizing new terms. The goal of

■ Table 2-1 | Magnitude and Intensity

Magnitude Difference	Approximate Intensity Ratio
0	1
1	2.5
2	6.3
3	16
4	40
5	100
6	250
7	630
8	1600
9	4000
10	10,000
⋮	⋮
15	1,000,000
20	100,000,000
25	10,000,000,000
⋮	⋮

Scientific Models

How can a scientific model be useful if it isn't entirely true? A scientific model is a carefully devised conception of how something works, a framework that helps scientists think about some aspect of nature, just as the celestial sphere helps astronomers think about the motions of the sky.

Chemists, for example, use colored balls to represent atoms and sticks to represent the bonds between them, kind of like Tinkertoys. Using these molecular models, chemists can see the three-dimensional shape of molecules and understand how the atoms interconnect. The molecular model of DNA proposed by Watson and Crick in 1953 led to our modern understanding of the mechanisms of genetics. You have probably seen elaborate ball-and-stick models of DNA, but does the molecule really look like Tinkertoys? No, but the model is both simple enough and accurate enough to help scientists think about their theories.

A scientific model is not a statement of truth; it does not have to be precisely true to be useful. In an idealized model, some complex aspects of nature can be simplified or omitted. The ball-and-stick model of a molecule doesn't show the relative strength of the chemical bonds, for instance. A model gives scientists a way to think about some aspect of nature but need not be true in every detail.

When you use a scientific model, it is important to remember the limitations of that model. If you begin to think of a model as true, it can be misleading instead of helpful. The celestial sphere, for instance, can help you think about the sky, but you must remember that it is only a model. The universe is much larger and much more interesting than this ancient scientific model of the heavens.

Balls represent atoms and rods represent chemical bonds in this model of a DNA molecule.
(Digital Vision/Getty Images)



science is to understand nature, not to memorize definitions. Study the diagrams and see how the geometry of the celestial sphere and its motions produce the sky you see above you.

The celestial sphere is an example of a **scientific model**, a common feature of scientific thought (**How Do We Know? 2-1**). Notice that a scientific model does not have to be true to be useful. You will encounter many scientific models in the chapters that follow, and you will discover that some of the most useful models are highly simplified descriptions of the true facts.

This is a good time to eliminate a couple of **Common Misconceptions**. Lots of people, without thinking about it much, assume that the stars are not in the sky during the daytime. The stars are actually there day and night; they are just invisible during the day because the sky is lit up by sunlight. Also, many people insist that Favorite Star Polaris is the brightest star in the sky. It is actually the 51st visually brightest star. You now know that Polaris is important because of its position, not because of its brightness.

In addition to causing the obvious daily motion of the sky, Earth's rotation conceals a very slow celestial motion that can be detected only over centuries.

Precession

Over 2000 years ago, Hipparchus compared a few of his star positions with those recorded nearly two centuries earlier and realized that the celestial poles and equator were slowly moving across the sky. Later astronomers understood that this motion is caused by the top-like motion of Earth.

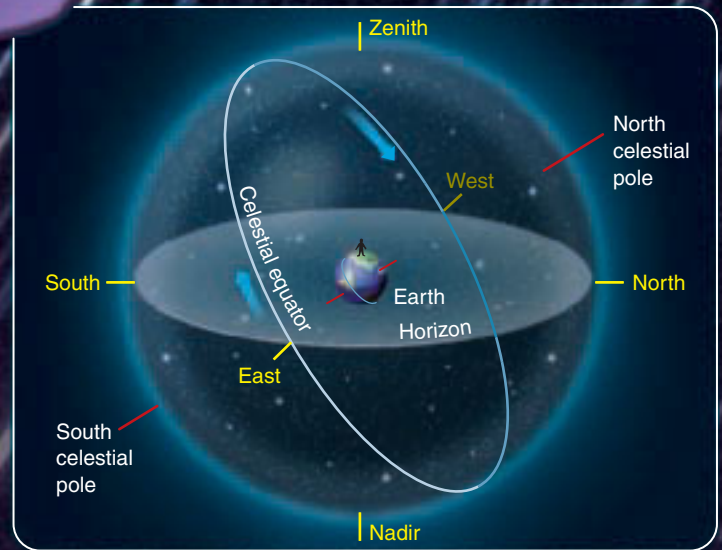
If you have ever played with a gyroscope or top, you have seen how the spinning mass resists any sudden change in the direction of its axis of rotation. The more massive the top and the more rapidly it spins, the more it resists your efforts to twist it out of position. But you probably recall that even the most rapidly spinning top slowly swings its axis around in a circle... The weight of the top tends to make it tip over, and this combines with its rapid rotation to make its axis sweep out the shape of a cone in a motion called **precession** (■ Figure 2-7a). In later chapters, you will learn that many celestial bodies precess.

Earth spins like a giant top, but it does not spin upright in its orbit; it is tipped 23.5° from vertical. Earth's large mass and rapid rotation keep its axis of rotation pointed toward a spot near the star Polaris, and the axis would not wander if it were not for precession.

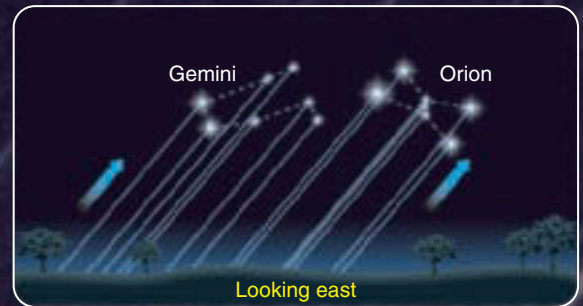
The Sky Around You

1 The eastward rotation of Earth causes the sun, moon, and stars to move westward in the sky as if the **celestial sphere** were rotating westward around Earth. From any location on Earth you see only half of the celestial sphere, the half above the **horizon**. The **zenith** marks the top of the sky above your head, and the **nadir** marks the bottom of the sky directly under your feet. The drawing at right shows the view for an observer in North America. An observer in South America would have a dramatically different horizon, zenith, and nadir.

The apparent pivot points are the **north celestial pole** and the **south celestial pole** located directly above Earth's north and south poles. Halfway between the celestial poles lies the **celestial equator**. Earth's rotation defines the directions you use every day. The **north point** and **south point** are the points on the horizon closest to the celestial poles. The **east point** and the **west point** lie halfway between the north and south points. The celestial equator always touches the horizon at the east and west points.



Looking north



Looking east



Looking south

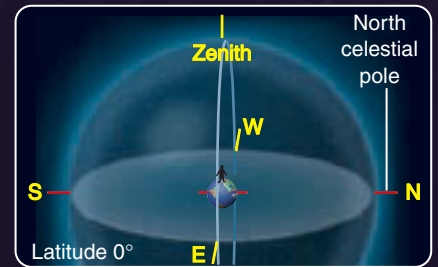
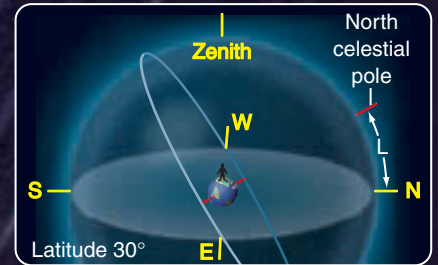
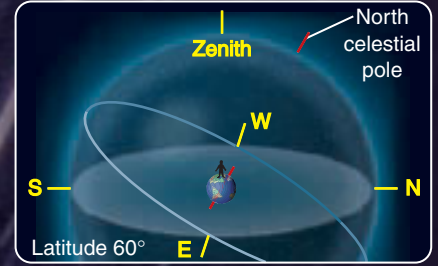
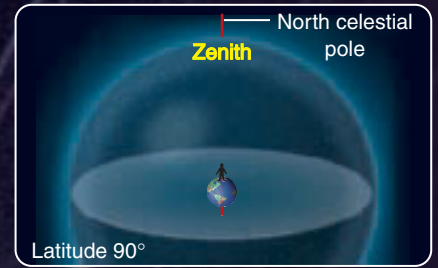
1a This time exposure of about 30 minutes shows stars as streaks, called star trails, rising behind an observatory dome. The camera was facing northeast to take this photo. The motion you see in the sky depends on which direction you look, as shown at right. Looking north, you see the Favorite Star Polaris, the North Star, located near the north celestial pole. As the sky appears to rotate westward, Polaris hardly moves, but other stars circle the celestial pole. Looking south from a location in North America, you can see stars circling the south celestial pole, which is invisible below the southern horizon.

Astronomers measure distance across the sky as angles.

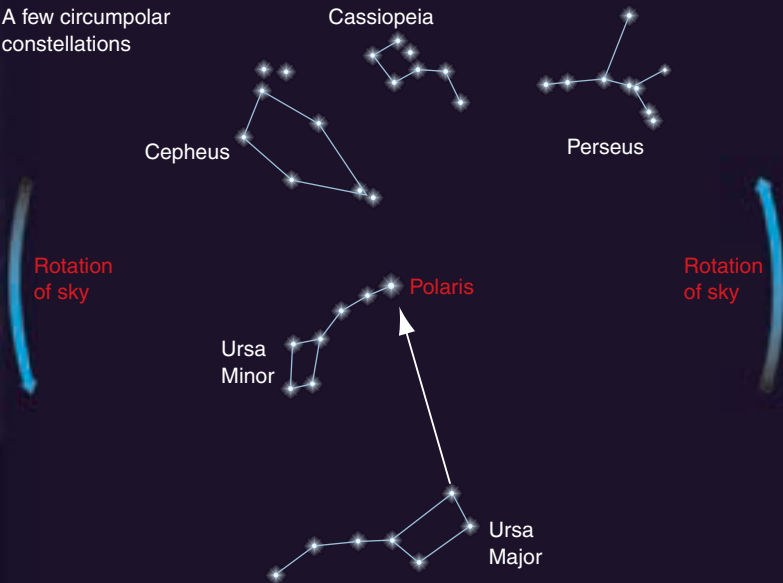


2 Astronomers might say, “The star was only 2 degrees from the moon.” Of course, the stars are much farther away than the moon, but when you think of the celestial sphere, you can measure distances *on the sky* as **angular distances** in degrees, minutes of arc, and seconds of arc. An **arc minute** is 1/60th of a degree, and an **arc second** is 1/60th of a minute of arc. Then the **angular diameter** of an object is the angular distance from one edge to the other. The sun and moon are each about half a degree in diameter, and the bowl of the Big Dipper is about 10° wide. In order to distinguish these units from the similarly named units of time, astronomers refer to small angles in arc minutes or arc seconds. The word *arc* indicates that the numbers refer to angles and not time.

3 What you see in the sky depends on your latitude as shown at right. Imagine that you begin a journey in the ice and snow at Earth’s North Pole with the north celestial pole directly overhead. As you walk southward, the celestial pole moves toward the horizon, and you can see farther into the southern sky. The angular distance from the horizon to the north celestial pole always equals your latitude (*L*)—the basis for celestial navigation. As you cross Earth’s equator, the celestial equator would pass through your zenith, and the north celestial pole would sink below your northern horizon.



A few circumpolar constellations



3a **Circumpolar constellations** are those that never rise or set. From mid-northern latitudes, as shown at left, you see a number of familiar constellations circling Polaris and never dipping below the horizon. As the sky rotates, the pointer stars at the front of the Big Dipper always point toward Polaris. Circumpolar constellations near the south celestial pole never rise as seen from mid-northern latitudes. From a high latitude such as Norway, you would have more circumpolar constellations, and from Quito, Ecuador, located on Earth’s equator, you would have no circumpolar constellations at all.



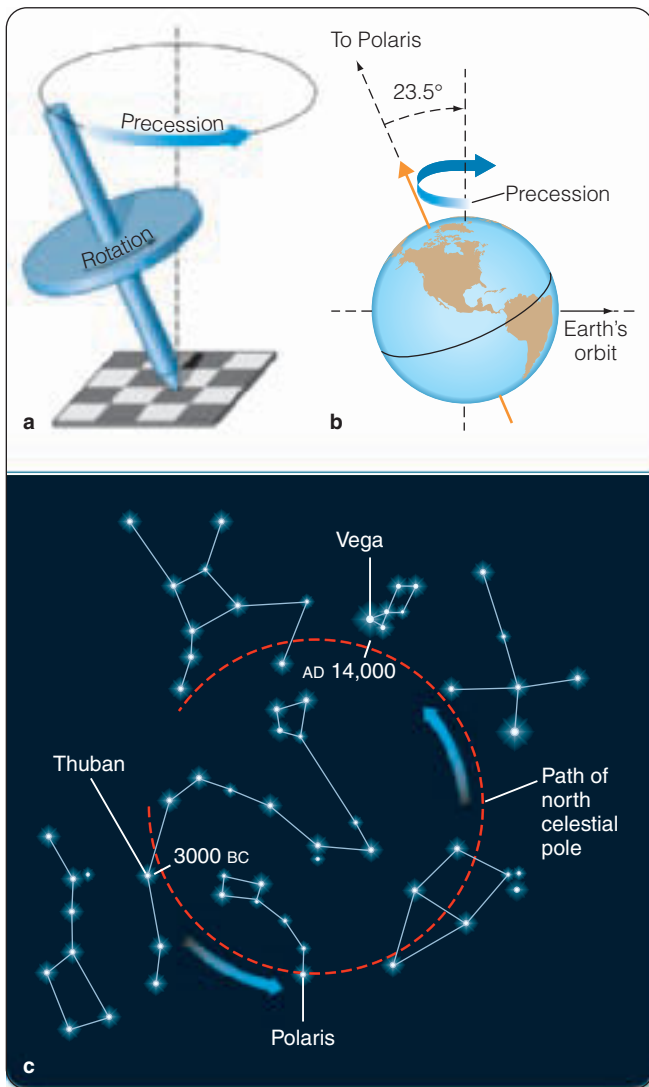
Because of its rotation, Earth has a slight bulge around its middle, and the gravity of the sun and moon pull on this bulge, tending to twist Earth's axis "upright" relative to its orbit. If Earth were a perfect sphere, it would not get twisted. Notice that gravity tends to make the top fall over, but it tends to twist Earth upright in its orbit. In both cases, the twisting of the axis of rotation combines with the rotation of the object and causes precession. Earth's axis precesses, taking about 26,000 years for one cycle (Figure 2-7b).

Because the locations of the celestial poles and equator are defined by Earth's rotational axis, precession slowly moves these reference marks. You would notice no change at all from night to night or year to year, but precise measurements can reveal the

slow precession of the celestial poles and the resulting change in orientation of the celestial equator.

Over centuries, precession has dramatic effects. Egyptian records show that 4800 years ago the north celestial pole was near the star Thuban (alpha Draconis). The pole is now approaching Polaris and will be closest to it in about the year 2100. In about 12,000 years, the pole will have moved to within 5° of Vega (alpha Lyrae). Next time you glance at Favorite Star Vega, remind yourself that it will someday be a very impressive north star. Figure 2-7c shows the path followed by the north celestial pole.

2-3 The Cycles of the Sun



■ **Figure 2-7**

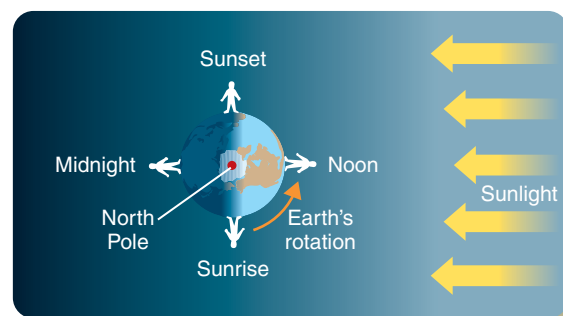
Precession. (a) A spinning top precesses in a conical motion around the perpendicular to the floor because its weight tends to make it fall over. (b) Earth precesses around the perpendicular to its orbit because the gravity of the sun and moon acting on Earth's equatorial bulge tend to twist it upright. (c) Precession causes the north celestial pole to move slowly among the stars, completing a circle in 26,000 years.

EARTH'S ROTATION ON ITS AXIS causes the cycle of day and night, but it is its motion around the sun in its orbit that defines the year. Notice an important distinction. **Rotation** is the turning of a body on its axis, but **revolution** means the motion of a body around a point outside the body. Consequently, astronomers are careful to say Earth rotates once a day on its axis and revolves once a year around the sun.

Because day and night are caused by the rotation of Earth, your time of day depends on your location on Earth. You can see this if you watch live international news. It may be lunchtime where you are, but for a newscaster in the Middle East, it can already be dark. In ■ Figure 2-8, you can see that four people in different places on Earth have different times of day.

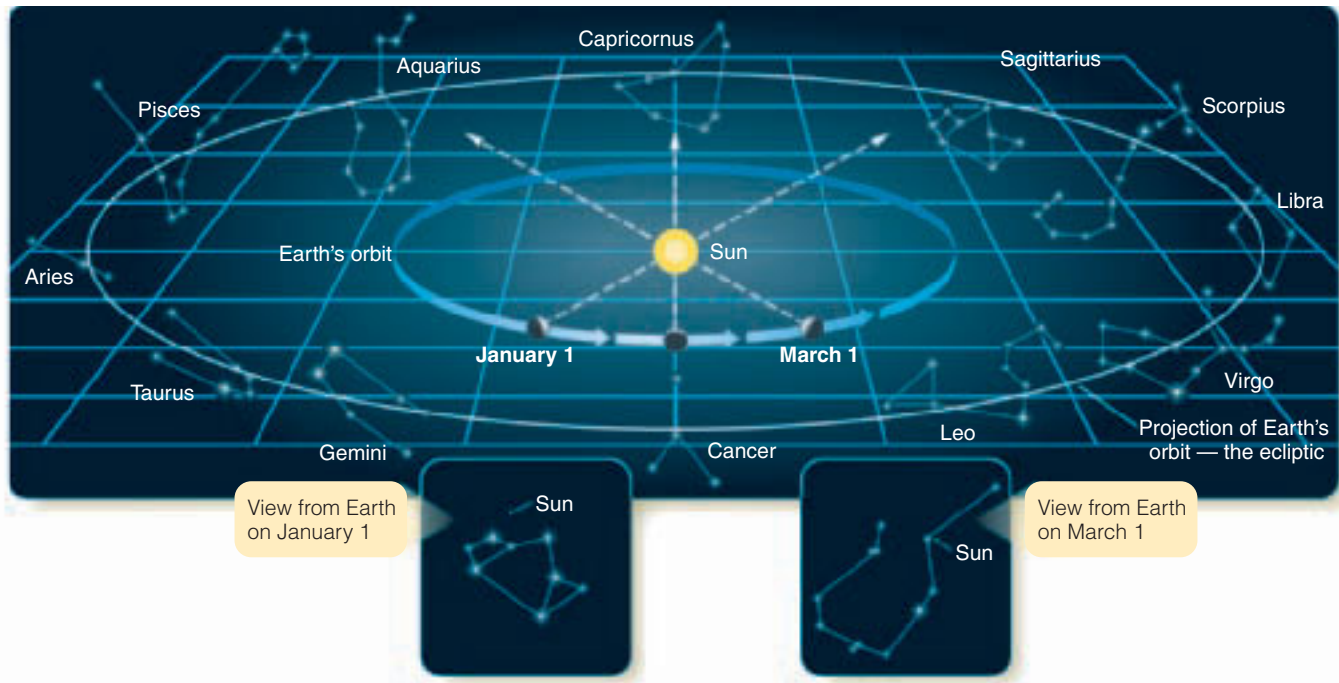
The Annual Motion of the Sun

Even in the daytime, the sky is filled with stars, but the glare of sunlight fills Earth's atmosphere with scattered light, and you can see only the brilliant sun. If the sun were fainter, you would be able to see it rise in the morning in front of the stars. During the day, you would see the sun and the stars moving westward, and the sun would eventually set in front of the same stars. If you watched carefully as the day passed, you would notice that the sun was creeping slowly eastward against the background of stars.



■ **Figure 2-8**

Looking down on Earth from above the North Pole shows how the time of day or night depends on your location on Earth.



■ **Figure 2-9**

Earth's orbit is a nearly perfect circle, but it is shown in an inclined view in this diagram and consequently looks oval. Earth's motion around the sun makes the sun appear to move against the background of the stars. Earth's circular orbit is thus projected on the sky as the circular path of the sun, the ecliptic. If you could see the stars in the daytime, you would notice the sun crossing in front of the distant constellations as Earth moves along its orbit.

It would move a distance roughly equal to its own diameter between sunrise and sunset. This motion is caused by the motion of Earth in its nearly circular orbit around the sun.

For example, in January, you would see the sun in front of the constellation Sagittarius (■ Figure 2-9). As Earth moves along its circular orbit, the sun appears to move eastward among the stars. By March, you would see it in front of Aquarius.

Although people often say the sun is “in Sagittarius” or “in Aquarius,” it isn't really correct to say the sun is “in” a constellation. The sun is only 1 AU away, and the stars visible in the sky are at least a million times more distant. Nevertheless, in March of each year, the sun crosses in front of the stars that make up Aquarius, and people conventionally use the expression, “The sun is in Aquarius.”

The apparent path of the sun against the background of stars is called the **ecliptic**. If the sky were a great screen, the ecliptic would be the shadow cast by Earth's orbit. That is why the ecliptic is often called the projection of Earth's orbit on the sky.

Earth circles the sun in 365.25 days and, consequently, the sun appears to circle the sky in the same period. That means the sun, traveling 360° around the ecliptic in 365.25 days, travels about 1° eastward in 24 hours, about twice its angular diameter. You don't notice this apparent motion of the sun because you can't see the stars in the daytime, but it does have an important consequence that you do notice—the seasons.

The Seasons

Earth would not experience seasons if it rotated upright in its orbit, but because its axis of rotation is tipped 23.4° from the perpendicular to its orbit, it has seasons. Study **The Cycle of the Seasons** on pages 22–23 and notice two important principles and six new terms:

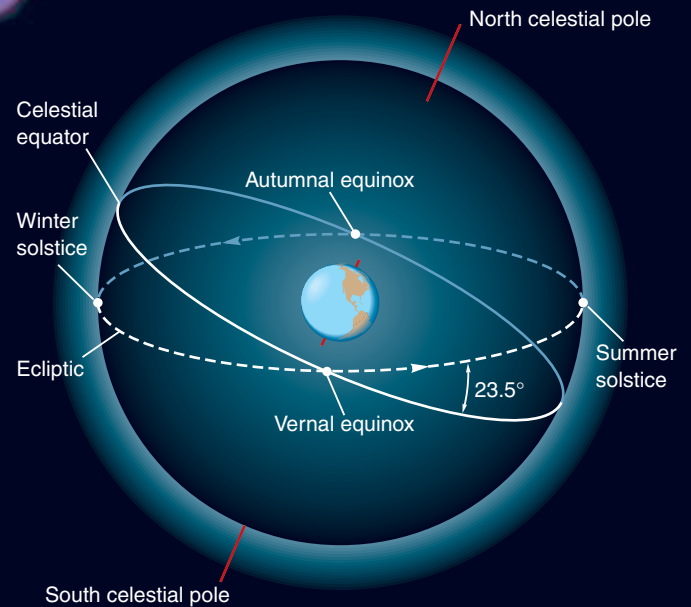
- 1 Because Earth's axis of rotation is inclined 23.4° , the sun moves into the northern sky in the spring and into the southern sky in the fall. That causes the cycle of the seasons. Notice how the *vernal equinox*, the *summer solstice*, the *autumnal equinox*, and the *winter solstice* mark the beginning of the seasons. Further, notice the very minor effects of Earth's slightly elliptical orbit as it travels from *perihelion* to *aphelion*.
- 2 Earth goes through a cycle of seasons because of changes in the amount of solar energy that Earth's northern and southern hemispheres receive at different times of the year. Because of circulation patterns in Earth's atmosphere, the northern and southern hemispheres are mostly isolated from each other and exchange little heat. When one hemisphere receives more solar energy than the other, it grows rapidly warmer.

Notice that the seasons in Earth's southern hemisphere are reversed with respect to those in the northern hemisphere. Australia and other lands in the southern hemisphere experience

The Cycle of the Seasons

1 You can use the celestial sphere to help you think about the seasons. The celestial equator is the projection of Earth's equator on the sky, and the ecliptic is the projection of Earth's orbit on the sky. Because Earth is tipped in its orbit, the ecliptic and equator are inclined to each other by 23.5° as shown at right. As the sun moves eastward around the sky, it spends half the year in the southern half of the sky and half the year in the northern half. That causes the seasons.

The sun crosses the celestial equator going northward at the point called the **vernal equinox**. The sun is at its farthest north at the point called the **summer solstice**. It crosses the celestial equator going southward at the **autumnal equinox** and reaches its most southern point at the **winter solstice**.



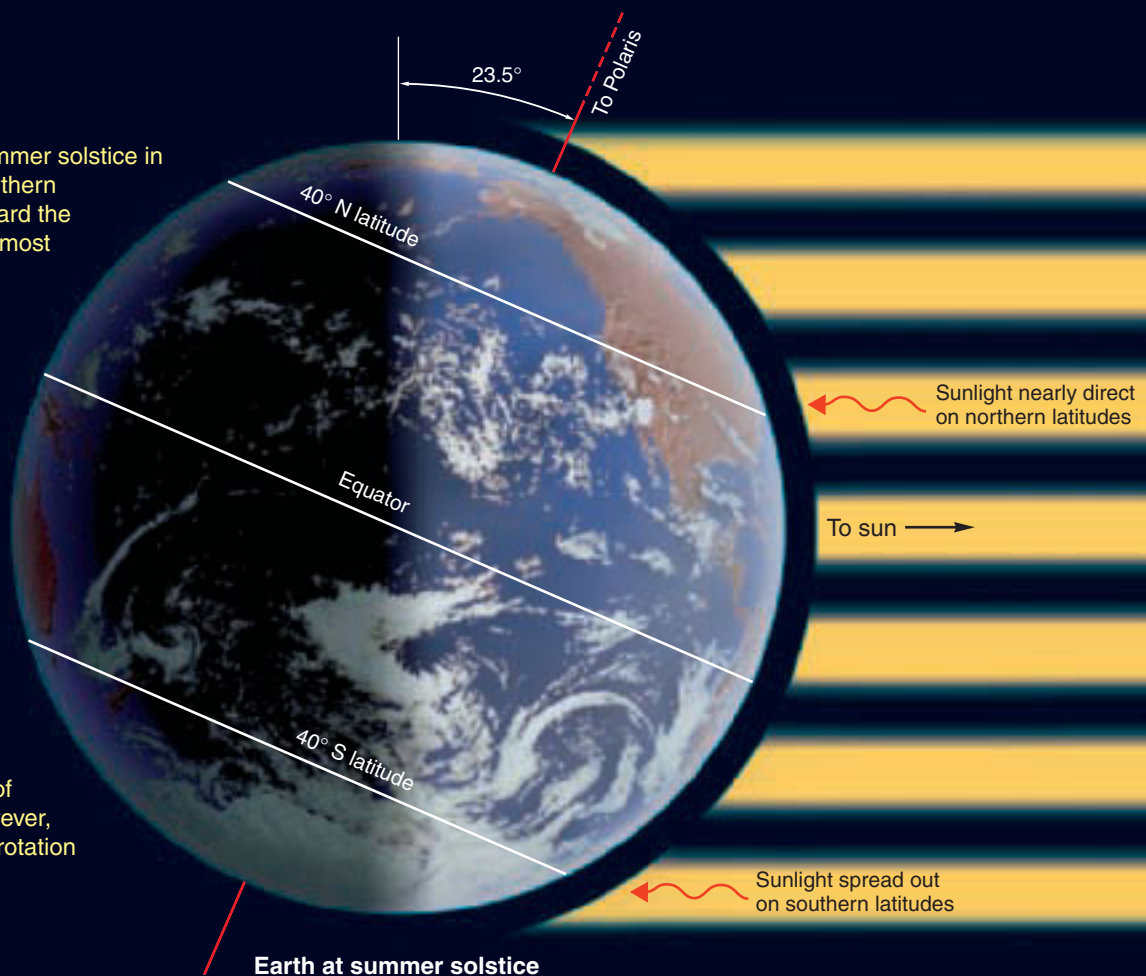
1a The seasons are defined by the dates when the sun crosses these four points, as shown in the table at the right. *Equinox* comes from the word for "equal"; the day of an equinox has equal amounts of daylight and darkness. *Solstice* comes from the words meaning "sun" and "stationary." *Vernal* comes from the word for "green." The "green" equinox marks the beginning of spring.

Event	Date*	Season
Vernal equinox	March 20	Spring begins
Summer solstice	June 22	Summer begins
Autumnal equinox	September 22	Autumn begins
Winter solstice	December 22	Winter begins

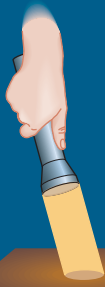
* Give or take a day due to leap year and other factors.

1b On the day of the summer solstice in late June, Earth's northern hemisphere is inclined toward the sun, and sunlight shines almost straight down at northern latitudes. At southern latitudes, sunlight strikes the ground at an angle and spreads out. North America has warm weather, and South America has cool weather.

Earth's axis of rotation points toward Polaris, and, like a top, the spinning Earth holds its axis fixed as it orbits the sun. On one side of the sun, Earth's northern hemisphere leans toward the sun; on the other side of its orbit, it leans away. However, the direction of the axis of rotation does not change.

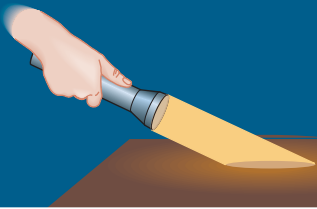


Summer solstice light



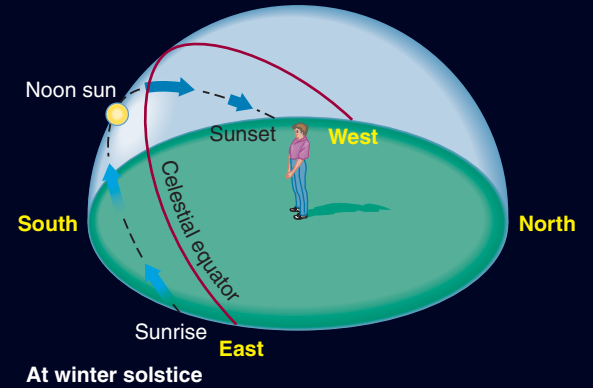
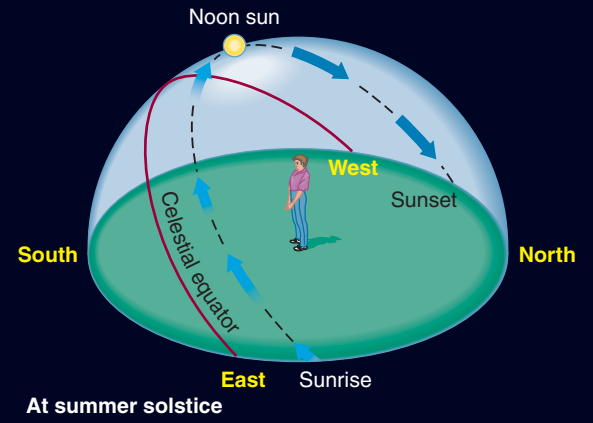
1c Light striking the ground at a steep angle spreads out less than light striking the ground at a shallow angle. Light from the summer solstice sun strikes northern latitudes from nearly overhead and is concentrated.

Winter solstice light



Light from the winter solstice sun strikes northern latitudes at a much shallower angle and spreads out. The same amount of energy is spread over a larger area, so the ground receives less energy from the winter sun.

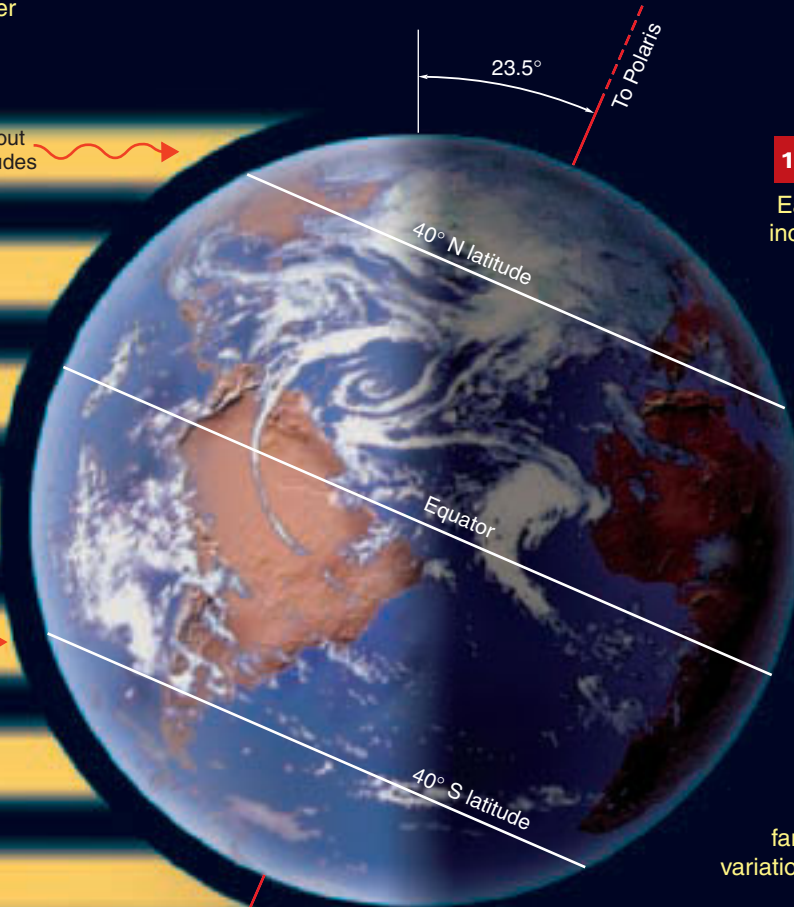
2 The two causes of the seasons are shown at right for someone in the northern hemisphere. First, the noon summer sun is higher in the sky and the winter sun is lower, as shown by the longer winter shadows. Thus winter sunlight is more spread out. Second, the summer sun rises in the northeast and sets in the northwest, spending more than 12 hours in the sky. The winter sun rises in the southeast and sets in the southwest, spending less than 12 hours in the sky. Both of these effects mean that northern latitudes receive more energy from the summer sun, and summer days are warmer than winter days.



Sunlight spread out on northern latitudes

To sun

Sunlight nearly direct on southern latitudes



Earth at winter solstice

1d On the day of the winter solstice in late December, Earth's northern hemisphere is inclined away from the sun, and sunlight strikes the ground at an angle and spreads out. At southern latitudes, sunlight shines almost straight down and does not spread out. North America has cool weather and South America has warm weather.

Earth's orbit is only very slightly elliptical. About January 3, Earth is at **perihelion**, its closest point to the sun, when it is only 1.7 percent closer than average. About July 5, Earth is at **aphelion**, its most distant point from the sun, when it is only 1.7 percent farther than average. This small variation does not significantly affect the seasons.

winter from June 22 to September 22, and summer from December 22 to March 20.

Now you can set your friends straight if they mention two of the most **Common Misconceptions** about the seasons. First, the seasons don't occur because Earth moves closer to or farther from the sun. If that were the cause, both of Earth's hemispheres would experience winter at the same time, and that's not what happens. Earth's orbit is nearly circular. Earth is only 1.7 percent closer to the sun in January and 1.7 percent farther away in July, and that small variation isn't enough to cause the seasons. Rather, the seasons arise because Earth's axis is not perpendicular to its orbit.

Here's a second **Common Misconception**: It is not easier to stand a raw egg on end on the day of the vernal equinox. Have you heard that one? Radio and TV personalities love to talk about it, but it just isn't true. It is one of the silliest misconceptions in science. You can stand a raw egg on end any day of the year if you have steady hands. (*Hint*: It helps to shake the egg really hard to break the yoke inside so it can settle to the bottom.)

In ancient times, the cycle of the seasons, especially the solstices and equinoxes, were celebrated with rituals and festivals. Shakespeare's play *A Midsummer Night's Dream* describes the enchantment of the summer solstice night. (In Shakespeare's time, the equinoxes and solstices were taken to mark the midpoints of the seasons.) Many North American Indians marked the summer solstice with ceremonies and dances. Early church officials placed Christmas day in late December to coincide with an earlier pagan celebration of the winter solstice.

The Motion of the Planets

The planets of our solar system produce no visible light of their own; they are visible only by reflected sunlight. Mercury, Venus, Mars, Jupiter, and Saturn are all easily visible to the unaided eye and look like stars, but Uranus is usually too faint to be seen, and Neptune is never bright enough.

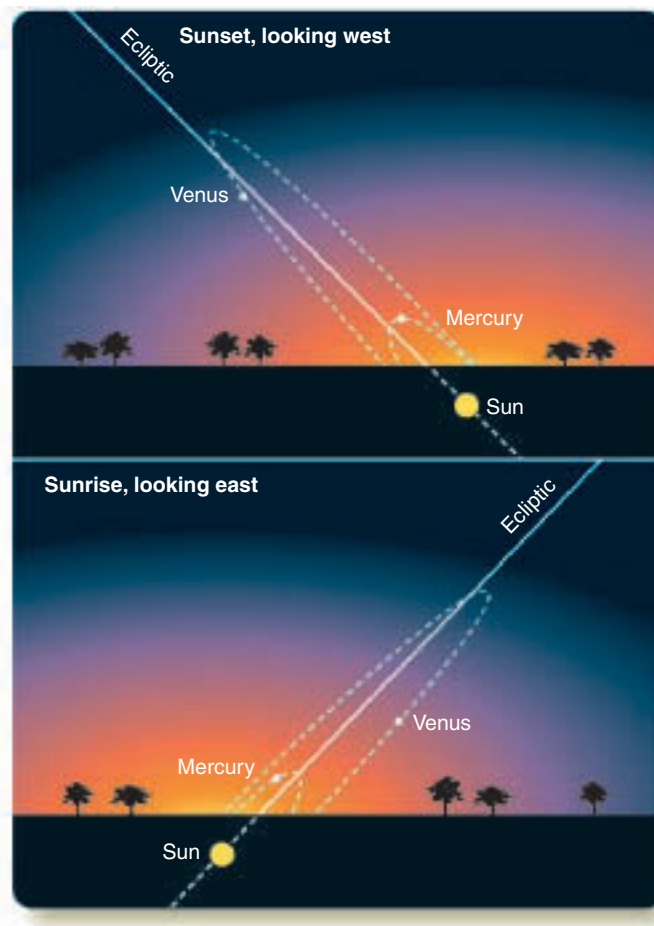
All of the planets of the solar system, including Earth, move in nearly circular orbits around the sun. If you were looking down on the solar system from the north celestial pole, you would see the planets moving in the same counterclockwise direction around their orbits, with the planets farthest from the sun moving the slowest. Seen from Earth, the outer planets move slowly eastward* along the ecliptic. In fact, the word *planet* comes from the Greek word meaning "wanderer." Mars moves completely around the ecliptic in slightly less than 2 years, but Saturn, being farther from the sun, takes nearly 30 years.

Mercury and Venus also stay near the ecliptic, but they move differently from the other planets. They have orbits inside Earth's orbit, and that means they are never seen far from the sun in the sky. Observed from Earth, they move eastward away from the sun and then back toward the sun, crossing the near part of their

*You will discover occasional exceptions to this eastward motion in Chapter 4.

orbit. They continue moving westward away from the sun and then move back crossing the far part of their orbit before they move out east of the sun again. To find one of these planets, you need to look above the western horizon just after sunset or above the eastern horizon just before sunrise. Venus is easier to locate because it is brighter and because its larger orbit carries it higher above the horizon than does Mercury's (■ Figure 2-10). Mercury's orbit is so small that it can never get farther than 28° from the sun. Consequently, it is hard to see against the sun's glare and is often hidden in the clouds and haze near the horizon.

By tradition, any planet visible in the evening sky is called an **evening star**, even though planets are not stars. Similarly, any planet visible in the sky shortly before sunrise is called a **morning star**. Perhaps the most beautiful is Venus, which can become as bright as magnitude -4.7 . As Venus moves around its orbit, it can dominate the western sky each evening for many weeks, but eventually its orbit carries it back toward the sun, and it is lost in the haze near the horizon. In a few weeks, it reappears in the dawn sky, a brilliant morning star.



■ **Figure 2-10**

Mercury and Venus follow orbits that keep them near the sun, and they are visible only soon after sunset or before sunrise when the brilliance of the sun is hidden below the horizon. Venus takes 584 days to move from the morning sky to the evening sky and back again, but Mercury zips around in only 116 days.

Pseudoscience

What is the difference between a science and a pseudoscience? Astronomers have a low opinion of beliefs such as astrology, mostly because they are groundless but also because they *pretend* to be a science. They are pseudosciences, from the Greek *pseudo*, meaning false.

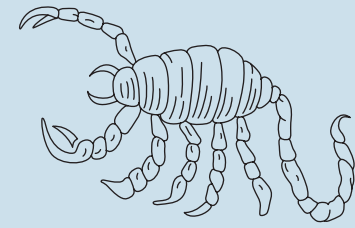
A **pseudoscience** is a set of beliefs that appear to be based on scientific ideas but that fail to obey the most basic rules of science. For example, in the 1970s a claim was made that pyramidal shapes focus cosmic forces on anything underneath and might even have healing properties. For example, it was claimed that a pyramid made of paper, plastic, or other materials would preserve fruit, sharpen razor blades, and do other miraculous things. Many books promoted the idea of the special power of pyramids, and this idea led to a popular fad.

A key characteristic of science is that its claims can be tested and verified. In this case, simple experiments showed that any shape, not just a pyramid, protects a piece of fruit from airborne spores and allows it to dry

without rotting. Likewise, any shape allows oxidation to improve the cutting edge of a razor blade. Because experimental evidence contradicted the claim and because supporters of the theory declined to abandon or revise their claims, you can recognize pyramid power as a pseudoscience. Disregard of contradictory evidence and alternate theories is a sure sign of a pseudoscience.

Pseudoscientific claims can be self-fulfilling. For example, some believers in pyramid power slept under pyramidal tents to improve their rest. There is no logical mechanism by which such a tent could affect a sleeper, but because people wanted and expected the claim to be true they reported that they slept more soundly. Vague claims based on personal testimony that cannot be tested are another sign of a pseudoscience.

Astrology is another pseudoscience. It has been tested over and over for centuries, and it doesn't work. Nevertheless, many people believe in astrology despite contradictory evidence.



Astrology may be the oldest pseudoscience.

Many pseudosciences appeal to our need to understand and control the world around us. Some such claims involve medical cures, ranging from using magnetic bracelets and crystals to focus mystical power to astonishingly expensive, illegal, and dangerous treatments for cancer. Logic is a stranger to pseudoscience, but human fears and needs are not.

The cycles of the sky are so impressive that it is not surprising that people have strong feelings about them. Ancient peoples saw the motion of the sun around the ecliptic as a powerful influence on their daily lives, and the motion of the planets along the ecliptic seemed similarly meaningful. The ancient superstition of astrology is based on the cycles of the sun and planets around the sky. You have probably heard of the **zodiac**, a band around the sky extending 9 degrees above and below the ecliptic. The signs of the zodiac take their names from the 12 principal constellations along the ecliptic. A **horoscope** is just a diagram showing the location of the sun, moon, and planets around the ecliptic and their position above or below the horizon for a given date and time. Centuries ago, astrology was an important part of astronomy, but the two are now almost exact opposites—astronomy is a science that depends on evidence, and astrology is a superstition that survives in spite of evidence (**How Do We Know? 2-2**). The signs of the zodiac are no longer important in astronomy.

2-4 Astronomical Influences on Earth's Climate

THE SEASONS ARE PRODUCED by the annual motion of Earth around the sun, but subtle changes in that motion can have dramatic effects on climate. You don't notice these changes during

your lifetime; but, over thousands of years, they can bury continents under glaciers.

Earth has gone through ice ages when the worldwide climate was cooler and dryer and thick layers of ice covered polar regions, extending partway to the equator. Between ice ages, Earth is warmer and there are no ice sheets even at the poles. Scientists have found evidence of at least four ice ages in Earth's past. One occurred 2.5 billion years ago, but the other three that have been identified have all occurred in the last billion years. There were probably others, but evidence of early ice ages is usually erased by more recent ice sheets. The lengths of ice ages range from a few tens of millions of years to a few hundred million years. The most recent ice age began only about 3 million years ago and is still going on. You are living during one of the periodic episodes during an ice age when Earth grows slightly warmer and the glaciers melt back and do not extend as far from the poles. The current warm period began about 12,000 years ago.

Ice ages seem to occur with a period of roughly 250 million years, and glaciers advance and melt back during ice ages in a complicated pattern that involves cycles of about 40,000 years and 100,000 years. (These cycles have no connection with global warming, which can produce changes in Earth's climate over just a few decades. Global warming is discussed in Chapter 20.) Evidence shows that these slow cycles of the ice ages have an astronomical origin.

The Hypothesis

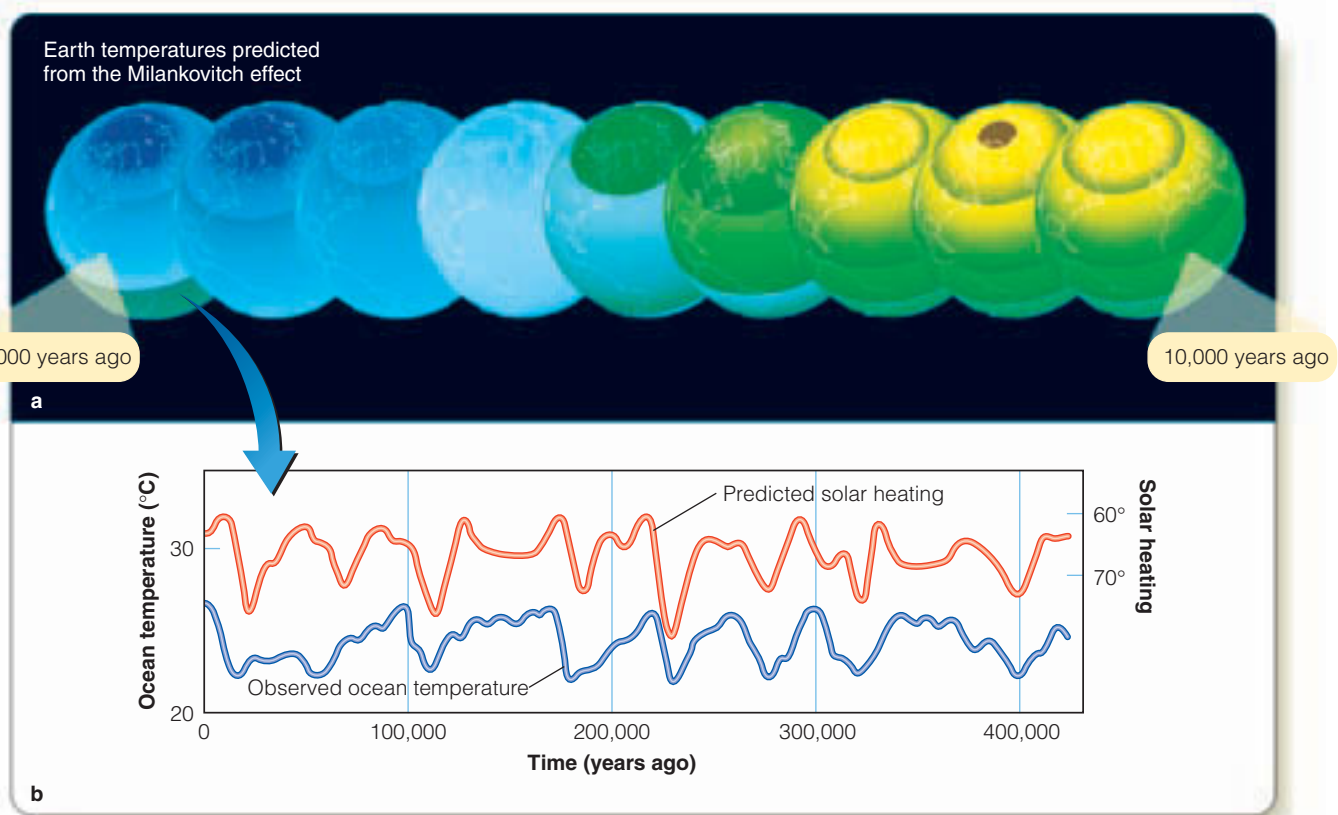
Sometimes a theory or hypothesis is proposed long before scientists can find the critical evidence to test it. That happened in 1920 when the Yugoslavian meteorologist Milutin Milankovitch proposed what became known as the **Milankovitch hypothesis**—that small changes in Earth's orbit, precession, and inclination affect Earth's climate and can cause ice ages. You should examine each of these motions separately.

First, Earth's orbit is only very slightly elliptical, but astronomers know that, because of gravitational interactions with the other planets, the elliptical shape varies slightly over a period of about 100,000 years. As you learned earlier in this chapter, Earth's orbit at present carries it 1.7 percent closer than average to the sun during northern hemisphere winters and 1.7 percent farther away in northern hemisphere summers. This makes northern winters very slightly warmer, and that is critical—most of the landmass where ice can accumulate is in the northern hemisphere. When Earth's orbit becomes more elliptical, northern summers might be too cool to melt all of the snow and ice from the previous winter. That would make glaciers grow larger.

A second factor is also at work. Precession causes Earth's axis to sweep around a cone with a period of about 26,000 years, and that gradually changes the points in Earth's orbit where a given hemisphere experiences the seasons. Northern hemisphere summers now occur when Earth is 1.7 percent farther from the sun, but in 13,000 years northern summers will occur on the other side of Earth's orbit where Earth is 1.7 percent closer to the sun. Northern summers will be warmer, which could melt all of the previous winter's snow and ice and prevent the growth of glaciers.

The third factor is the inclination of Earth's equator to its orbit, currently at 23.4° . Because of gravitational tugs of the moon, sun, and even the other planets, this angle varies from 22° to 24° , with a period of roughly 41,000 years. When the inclination is greater, seasons are more severe.

In 1920, Milankovitch proposed that these three factors cycle against each other to produce complex periodic variations in Earth's climate and the advance and retreat of glaciers (■ Figure 2-11a). No evidence was available to test the theory in 1920, however, and scientists treated it with skepticism. Many thought it was laughable.



■ **Figure 2-11**

(a) Mathematical models of the Milankovitch effect can be used to predict temperatures on Earth over time. In these Earth globes, cool temperatures are represented by violet and blue and warm temperatures by yellow and red. These globes show the warming that occurred beginning 25,000 years ago, which ended the last ice age about 12,000 years ago. (Courtesy Arizona State University, Computer Science and Geography Departments) (b) Over the last 400,000 years, changes in ocean temperatures measured from fossils found in sediment layers from the seabed approximately match calculated changes in solar heating. (Adapted from Cesare Emiliani)

Evidence as the Foundation of Science

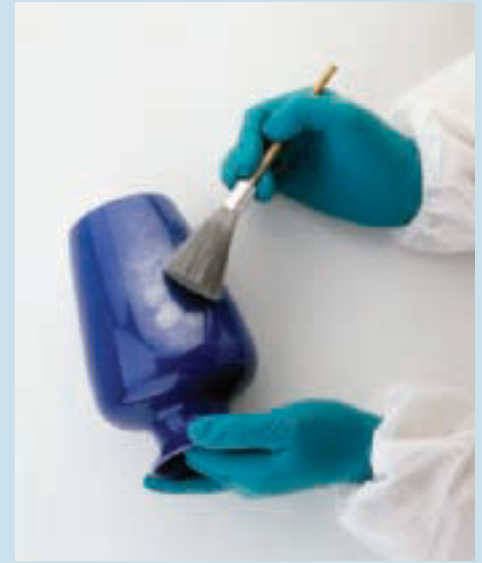
Why is evidence critical in science? From colliding galaxies to the inner workings of atoms, scientists love to speculate and devise theories, but all scientific knowledge is ultimately based on evidence from observations and experiments. Evidence is reality, and scientists constantly check their ideas against reality.

When you think of evidence, you probably think of criminal investigations in which detectives collect fingerprints and eyewitness accounts. In court, that evidence is used to try to understand the crime, but there is a key difference in how lawyers and scientists use evidence. A defense attorney can call a witness and intentionally fail to ask a question that would reveal evidence harmful to the defendant. In contrast, the scientist must be objective and not ignore any known evidence.

The attorney is presenting only one side of the case, but the scientist is searching for the truth. In a sense, the scientist must deal with the evidence as both the prosecution and the defense.

It is a characteristic of scientific knowledge that it is supported by evidence. A scientific statement is more than an opinion or a speculation because it has been tested objectively against reality.

As you read about any science, look for the evidence in the form of observations and experiments. Every theory or conclusion should have supporting evidence. If you can find and understand the evidence, the science will make sense. All scientists, from astronomers to zoologists, demand evidence. You should, too.



Fingerprints are evidence to past events.
(Dorling Kindersly/Getty Images)

The Evidence

By the middle 1970s, Earth scientists were able to collect the data that Milankovitch had lacked. Oceanographers drilled deep into the seafloor to collect long cores of sediment. In the laboratory, geologists could take samples from different depths in the cores and determine the age of the samples and the temperature of the oceans when they were deposited on the seafloor. From this, scientists constructed a history of ocean temperatures that convincingly matched the predictions of the Milankovitch hypothesis (Figure 2-11b).

The evidence seemed very strong, and by the 1980s the Milankovitch hypothesis was widely considered the leading hypothesis. But science follows a mostly unstated set of rules that holds that a hypothesis must be tested over and over against all available evidence (**How Do We Know? 2-3**). In 1988, scientists discovered contradictory evidence.

For 500,000 years rainwater has collected in a deep crack in Nevada called Devil's Hole. That water has deposited the mineral calcite in layer on layer on the walls of the crack. It isn't easy to get to, and scientists had to dive with scuba gear to drill out samples of the calcite, but it was worth the effort. Back in the laboratory, they could determine the age of each layer in their core samples and the temperature of the rainwater that had formed the calcite in each layer. That gave them a history of temperatures at Devil's Hole that spanned many thousands of

years, and the results were a surprise. The evidence seemed to show that Earth had begun warming up thousands of years too early for the last ice age to have been caused by the Milankovitch cycles.

These contradictory findings are irritating because we humans naturally prefer certainty, but such circumstances are common in science. The disagreement between the ocean floor samples and the Devil's Hole samples triggered a scramble to understand the problem. Were the age determinations of one or the other set of samples wrong? Were the calculations of ancient temperatures wrong? Or were scientists misunderstanding the significance of the evidence?

In 1997, a new study of the ages of the samples confirmed that those from the ocean floor are correctly dated. But the same study found that the ages of the Devil's Hole samples are also correct. Evidently the temperatures at Devil's Hole record local climate changes in the region that became the southwestern United States. The ocean floor samples record global climate changes, and they fit well with the Milankovitch hypothesis. This has given scientists renewed confidence in the Milankovitch hypothesis, and although it is widely accepted today, it is still being tested whenever scientists can find more evidence.

As you review this section, notice that it is a **scientific argument**, a careful presentation of theory and evidence in a logical discussion. **How Do We Know? 2-4** expands on the ways

Scientific Arguments

How is a scientific argument different from an advertisement? Advertisements sometimes sound scientific, but they are fundamentally different from scientific arguments. An advertisement is designed to convince you to buy a product. “Our shampoo promises 85 percent shinier hair.” The statement may sound like science, but it isn’t a complete, honest discussion. “Shinier than what?” you might ask. An advertiser’s only goal is a sale.

Scientists construct arguments because they want to test their own ideas and give an accurate explanation of some aspect of nature. For example, in the 1960s, biologist E. O. Wilson presented a scientific argument to show that ants communicate by smells. The argument included a description of his careful observations and the ingenious experiments he had conducted to test his theory. He also considered other evidence and other theories

for ant communication. Scientists can include any evidence or theory that supports their claim, but they must observe one fundamental rule of science: They must be totally honest—they must include all of the evidence and all of the theories.

Scientists publish their work in scientific arguments, but they also think in scientific arguments. If, in thinking through his argument, Wilson had found a contradiction, he would have known he was on the wrong track. That is why scientific arguments must be complete and honest. Scientists who ignore inconvenient evidence or brush aside other theories are only fooling themselves.

A good scientific argument gives you all the information you need to decide for yourself whether the argument is correct. Wilson’s study of ant communication is now widely



Scientists have discovered that ants communicate with a large vocabulary of smells. (Eye of Science/Photo Researchers, Inc.)

understood and is being applied to other fields such as pest control and telecommunications networks.

scientists organize their ideas in logical arguments. Throughout this book, many chapter sections end with short reviews entitled “Scientific Argument.” These feature a review question, which is then analyzed in a scientific argument. A second question gives you a chance to build your own scientific argument on a related topic. You can use these “Scientific Argument” features to review chapter material, but also to practice thinking like a scientist.

SCIENTIFIC ARGUMENT

Why was it critical in testing the Milankovitch hypothesis to determine the ages of ocean sediment?

Ocean floors accumulate sediment year after year in thin layers. Scientists can drill into the ocean floor and collect cores of those sediment layers, and from chemical tests they can find the temperature of the seawater when each layer was deposited. Those observations of temperature could be used as reality checks for the climate temperatures predicted by the Milankovitch theory, but that meant the ages of the sediment layers had to be determined correctly. When a conflict arose with evidence from Devil’s Hole in Nevada, the age determinations of the samples were carefully reexamined and found to be correct.

After reviewing all of the evidence, scientists concluded that the ocean core samples do indeed support the Milankovitch hypothesis. Now construct your own argument. **What might the temperatures recorded at Devil’s Hole represent?**

What Are We? Along for the Ride

Human civilization is spread over the surface of planet Earth like a thin coat of paint. Great cities of skyscrapers and tangles of superhighways may seem impressive, but if you use your astronomical perspective, you can see that we humans are confined to the surface of our world.

The rotation of Earth creates a cycle of day and night that controls everything from TV schedules to the chemical workings of our brains. We wake and sleep within that 24-hour cycle of light and dark. Furthermore, Earth’s orbital motion around the sun, combined with the inclination of its axis, creates a yearly cycle of seasons, and we humans, along with every other living thing on Earth, have evolved to survive within those extremes of temperature. We protect ourselves from the largest extremes and have spread over most of Earth, hunting, gathering, and growing crops within the cycle of the seasons.

In recent times, we have begun to understand that conditions on Earth’s surface are not entirely stable. Slow changes in its motions produce a cycle of ice ages with irregular pulses of glaciation. All of recorded history, including all of the cities and superhighways that paint our globe, has occurred since the last glacial retreat only 12,000 years ago, so we humans have no recorded experience of Earth’s harshest climate. We have never experienced our planet’s icy personality. We are along for the ride and enjoying Earth’s good times.

Study and Review

Summary

- ▶ Astronomers divide the sky into 88 **constellations** (p. 12). Although the constellations originated in Greek and Middle Eastern mythology, the names are Latin. Even the modern constellations, added to fill in the spaces between the ancient figures, have Latin names. Named groups of stars that are not constellations are called **asterisms** (p. 13).
- ▶ The names of stars usually come from ancient Arabic, though modern astronomers often refer to a star by its constellation and a Greek letter assigned according to its brightness within the constellation.
- ▶ Astronomers refer to the brightness of stars using the **magnitude scale** (p. 14). First-magnitude stars are brighter than second-magnitude stars, which are brighter than third-magnitude stars, and so on. The magnitude you see when you look at a star in the sky is its **apparent visual magnitude, m_v** (p. 15), which includes only types of light visible to the human eye and does not take into account the star's distance from Earth.
- ▶ **Flux** (p. 15) is a measure of light energy related to intensity. The magnitude of a star is related directly to the flux of light received on Earth and so to its intensity.
- ▶ The **celestial sphere** (p. 18) is a **scientific model** (p. 17) of the sky, to which the stars appear to be attached. Because Earth rotates eastward, the celestial sphere appears to rotate westward on its axis.
- ▶ The **north** and **south celestial poles** (p. 18) are the pivots on which the sky appears to rotate, and they define the four directions around the **horizon** (p. 18): the **north, south, east, and west points** (p. 18). The point directly over head is the **zenith** (p. 18), and the point on the sky directly underfoot is the **nadir** (p. 18).
- ▶ The **celestial equator** (p. 17), an imaginary line around the sky above Earth's equator, divides the sky into northern and southern halves.
- ▶ Astronomers often refer to distances "on" the sky as if the stars, sun, moon, and planets were equivalent to spots painted on a plaster ceiling. These **angular distances** (p. 19), measured in degrees, **arc minutes** (p. 19), and **arc seconds** (p. 19), are unrelated to the true distance between the objects in light-years. The angular distance across an object is its **angular diameter** (p. 19).
- ▶ What you see of the celestial sphere depends on your latitude. Much of the southern hemisphere of the sky is not visible from northern latitudes. To see that part of the sky, you would have to travel southward over Earth's surface. **Circumpolar constellations** (p. 19) are those close enough to a celestial pole that they do not rise or set.
- ▶ The angular distance from the horizon to the north celestial pole always equals your latitude. This is the basis for celestial navigation.
- ▶ **Precession** (p. 17) is caused by the gravitational forces of the moon and sun acting on the equatorial bulge of the spinning Earth and causing its axis to sweep around in a conical motion like the motion of a top's axis. Earth's axis of rotation precesses with a period of 26,000 years, and consequently the celestial poles and celestial equator move slowly against the background of the stars.
- ▶ The **rotation** (p. 20) of Earth on its axis produces the cycle of day and night, and the **revolution** (p. 20) of Earth around the sun produces the cycle of the year.
- ▶ Because Earth orbits the sun, the sun appears to move eastward along the **ecliptic** (p. 21) through the constellations completing a circuit of the sky in a year. Because the ecliptic is tipped 23.4° to the celestial equator, the sun spends half the year in the northern celestial hemisphere and half in the southern celestial hemisphere.
- ▶ In each hemisphere's summer, the sun is above the horizon longer and shines more directly down on the ground. Both effects cause warmer

weather in that hemisphere and leave Earth's other hemisphere cooler. In each hemisphere's winter, the sun is above the sky fewer hours than in summer and shines less directly, so the winter hemisphere has colder weather, and the opposite hemisphere has summer. Consequently the seasons are reversed in Earth's southern hemisphere relative to the northern hemisphere.

- ▶ The beginning of spring, summer, winter, and fall are marked by the **vernal equinox** (p. 22), the **summer solstice** (p. 22), the **autumnal equinox** (p. 22), and the **winter solstice** (p. 22).
- ▶ Earth is slightly closer to the sun at **perihelion** (p. 23) in January and slightly farther away from the sun at **aphelion** (p. 23) in July. This has almost no effect on the seasons.
- ▶ The planets move generally eastward along the ecliptic, and all but Uranus and Neptune are visible to the unaided eye looking like stars. Mercury and Venus never wander far from the sun and are sometimes visible in the evening sky after sunset or in the dawn sky before sunrise.
- ▶ Planets visible in the sky at sunset are traditionally called **evening stars** (p. 24), and planets visible in the dawn sky are called **morning stars** (p. 24) even though they are not actually stars.
- ▶ The locations of the sun and planets along the **zodiac** (p. 25) are diagramed in a **horoscope** (p. 25), which is the bases for the ancient **pseudoscience** (p. 25) known as astrology.
- ▶ According to the **Milankovitch hypothesis** (p. 26), changes in the shape of Earth's orbit, in its precession, and in its axial tilt can alter the planet's heat balance and cause the cycle of ice ages. Evidence found in seafloor samples support the hypothesis, and it is widely accepted today.
- ▶ Scientists routinely test their own ideas by organizing theory and evidence into a **scientific argument** (p. 27).

Review Questions

1. Why are most modern constellations composed of faint stars or located in the southern sky?
2. How does the Greek-letter designation of a star give you clues to its location and brightness?
3. From your knowledge of stars names and constellations, which of the following stars in each pair is the brighter? Explain your answers.
 - a. Alpha Ursae Majoris; Epsilon Ursae Majoris
 - b. Epsilon Scorpii; Alpha Pegasus
 - c. Alpha Telescopium; Alpha Orionis
4. How did the magnitude system originate in a classification of stars by brightness?
5. What does the word *apparent* mean in *apparent visual magnitude*?
6. What does the word *visual* mean in *apparent visual magnitude*?
7. In what ways is the celestial sphere a scientific model?
8. If Earth did not rotate, could you define the celestial poles and celestial equator?
9. Where would you go on Earth if you wanted to be able to see both the north celestial pole and the south celestial pole at the same time?
10. Why does the number of circumpolar constellations depend on the latitude of the observer?
11. Explain two reasons why winter days are colder than summer days.
12. How do the seasons in Earth's southern hemisphere differ from those in the northern hemisphere?
13. Why should the eccentricity of Earth's orbit make winter in Earth's northern hemisphere different from winter in Earth's southern hemisphere?

14. **How Do We Know?** How can a scientific model be useful if it isn't a correct description of nature?
15. **How Do We Know?** In what way is astrology a pseudoscience?
16. **How Do We Know?** How is evidence a distinguishing characteristic of science?
17. **How Do We Know?** Why must a scientific argument dealing with some aspect of nature include all of the evidence?

Discussion Questions

1. All cultures on Earth named constellations. Why do you suppose this was such a common practice?
2. If you were lost at sea, you could find your approximate latitude by measuring the altitude of Polaris. But Polaris isn't exactly at the celestial pole. What else would you need to know to measure your latitude more accurately?
3. Do planets orbiting other stars have ecliptics? Could they have seasons?

Problems

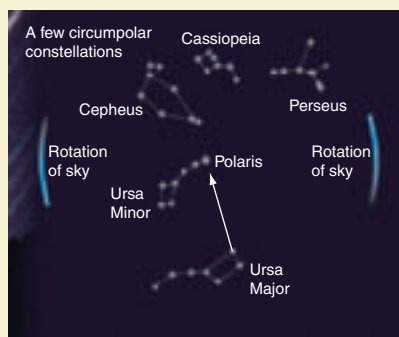
1. Star A has a magnitude of 2.5; Star B, 5.5; and Star C, 9.5. Which is brightest? Which are visible to the unaided eye? Which pair of stars has an intensity ratio of 16?
2. If one star is 6.3 times brighter than another star, how many magnitudes brighter is it?
3. If light from one star is 40 times more intense than light from another star, what is their difference in magnitudes?
4. If two stars differ by 7 magnitudes, what is their intensity ratio?
5. If two stars differ by 8.6 magnitudes, what is their intensity ratio?
6. If star A is magnitude 4 and star B is magnitude 9.6, which is brighter and by what factor?
7. By what factor is the sun brighter than the full moon? (*Hint:* See Figure 2-6.)
8. What is the angular distance from the north celestial pole to the point on the sky called the summer solstice? To the winter solstice?
9. If you are at a latitude of 35 degrees north of Earth's equator, what is the angular distance from the northern horizon up to the north celestial pole? From the southern horizon down to the south celestial pole?

Learning to Look

1. Find Sagittarius and Scorpius in the photograph that opens this chapter.
2. The stamp below shows the constellation Orion. Explain why this looks odd to residents of the northern hemisphere.

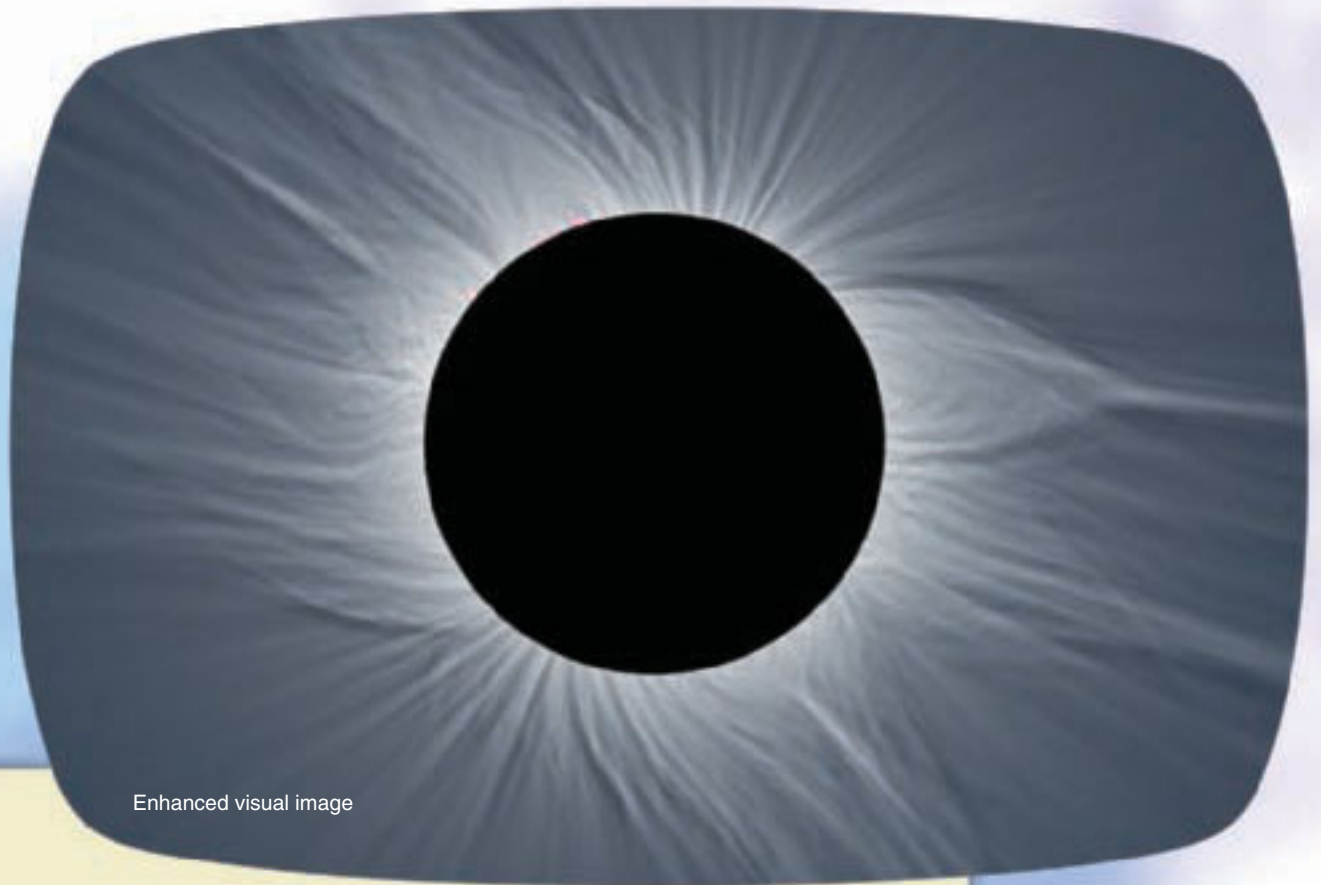


3. Imagine that the diagram below is a photograph taken in mid-September. Use the star charts at the back of this book to decide about what time of night the photo would have been taken.



3

Cycles of the Moon



Enhanced visual image

Guidepost

In the previous chapter, you studied the cycle of day and night and the cycle of the seasons. Now you are ready to study the brightest object in the night sky. The moon moves rapidly against the background of stars, changing its shape and occasionally producing spectacular events called eclipses. This chapter will help you answer four essential questions about Earth's satellite:

— **Why does the moon go through phases?**

— **What causes a lunar eclipse?**

— **What causes a solar eclipse?**

— **How can eclipses be predicted?**

Understanding the phases of the moon and eclipses will exercise your scientific imagination and help you enjoy the sight of the moon crossing the sky.

Once you have a 21st-century understanding of your world and its motion, you will be ready to read the next chapter, in which you will see how Renaissance astronomers analyzed what they saw in the sky, used their imaginations, and came to a revolutionary conclusion—that Earth is a planet.

A total solar eclipse is a lunar phenomenon. It occurs when the moon crosses in front of the sun and hides its brilliant surface. Then you can see the sun's extended atmosphere. (© F. Espenak, www.MrEclipse.com)

*Even a man who is pure in heart and says
his prayers by night*

*May become a wolf when the wolfbane
blooms and the moon shines full and bright.*

— PROVERB FROM OLD WOLFMAN MOVIES

DID ANYONE EVER WARN YOU, “Don’t stare at the moon—you’ll go crazy”? For centuries, the superstitious have associated the moon with insanity. The word *lunatic* comes from a time when even doctors thought that the insane were “moonstruck.” Of course, the moon does not cause madness, but it is so bright and moves so rapidly along the ecliptic that people *expect* it to affect them. It is, in fact, one of the most beautiful and dramatic objects in the sky.

3-1 The Changeable Moon

STARTING THIS EVENING, begin looking for the moon in the sky. As you watch for the moon on successive evenings, you will see it following its orbit around Earth and cycling through its phases as it has done for billions of years.

The Motion of the Moon

Just as the planets revolve counterclockwise around the sun as seen from the direction of the celestial north pole, the moon revolves counterclockwise around Earth. Because the moon’s orbit is tipped a little over 5 degrees from the plane of Earth’s orbit, the moon’s path takes it slightly north and then slightly south, but it is always somewhere near the ecliptic.

The moon moves rapidly against the background of the constellations. If you watch the moon for just an hour, you can see it move eastward by slightly more than its angular diameter. In the previous chapter, you learned that the moon is about 0.5° in angular diameter, and it moves eastward a bit more than 0.5° per hour. In 24 hours, it moves 13°. Thus, each night you see the moon about 13° eastward of its location the night before.

As the moon orbits around Earth, its shape changes from night to night in a month-long cycle.

The Cycle of Phases

The changing shape of the moon as it revolves around Earth is one of the most easily observed phenomena in astronomy. Study **The Phases of the Moon** on pages 34–35 and notice three important points and two new terms:

1 The moon always keeps the same side facing Earth. “The man in the moon” is produced by the familiar features on

the moon’s near side, but you never see the far side of the moon.

2 The changing shape of the moon as it passes through its cycle of phases is produced by sunlight illuminating different parts of the side of the moon you can see.

3 Notice the difference between the orbital period of the moon around Earth (*sidereal period*) and the length of the lunar phase cycle (*synodic period*). That difference is a good illustration of how your view from Earth is produced by the combined motions of Earth and other heavenly bodies, such as the sun and moon.

You can figure out where the moon will be in the sky by making a moon-phase dial from the middle diagram on page 34. Cover the lower half of the moon’s orbit with a sheet of paper and align the edge of the paper to pass through the word “Full” at the left and the word “New” at the right. Push a pin through the edge of the paper at Earth’s North Pole to make a pivot and, under the word “Full,” write on the paper “Eastern Horizon.” Under the word “New,” write “Western Horizon.” The paper now represents the horizon you see when you stand facing south. You can set your moon-phase dial for a given time by rotating the diagram behind the horizon-paper. For example, set the dial to sunset by turning the diagram until the human figure labeled “sunset” is standing at the top of the Earth globe; the dial shows, for example, that the full moon at sunset would be at the eastern horizon.

The phases of the moon are dramatic, and they have attracted a number of peculiar ideas. You have probably heard a number of **Common Misconceptions** about the moon. Sometimes people are surprised to see the moon in the daytime sky, and they think something has gone wrong! No, the gibbous moon is often visible in the daytime, although quarter moons and especially crescent moons can also be in the daytime sky but are harder to see when the sun is above the horizon. You may hear people mention “the dark side of the moon,” but you will be able to assure them that this is a misconception; there is no permanently dark side. Any location on the moon is sunlit for two weeks and is in darkness for two weeks as the moon rotates in sunlight. Finally, you have probably heard one of the strangest misconceptions about the moon: that people tend to act up at full moon. Actual statistical studies of records from schools, prisons, hospitals, and so on, show that it isn’t true. There are always a few people who misbehave; the moon has nothing to do with it.

For billions of years, the man in the moon has looked down on Earth. Ancient civilizations saw the same cycle of phases that you see (■ Figure 3-1), and even the dinosaurs may have noticed the changing phases of the moon. Occasionally, however, the moon displays more complicated moods when it turns copper-red in a lunar eclipse.



■ **Figure 3-1**

In this sequence of lunar phases, the moon cycles through its phases from crescent to full to crescent. You see the same face of the moon, the same mountains, craters, and plains, but the changing direction of sunlight produces the lunar phases.

3-2 Lunar Eclipses

IN CULTURES ALL AROUND THE WORLD, the sky is a symbol of order and power, and the moon is the regular counter of the passing days. So it is not surprising that people are startled and sometimes worried when they see the moon grow dark and angry-red. Such events are neither mysterious nor frightening once you understand how they arise. To begin, you can think about Earth's shadow.

Earth's Shadow

The orbit of the moon is tipped only a few degrees from the plane of Earth's orbit around the sun, and Earth's shadow points directly away from the sun also in the plane of Earth's orbit. A **lunar eclipse** can occur at full moon if the moon's path carries it through the shadow of Earth. That is unusual because most full moons pass north or south of Earth's shadow and there is no eclipse. If the moon enters Earth's shadow, sunlight is cut off, and the moon grows dim.

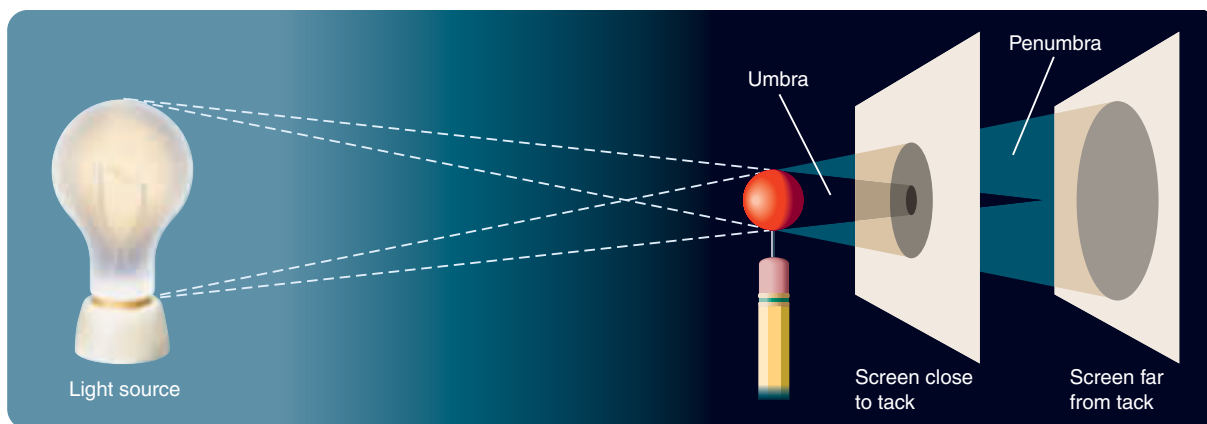
The shadow consists of two parts (■ Figure 3-2). The **umbra** is the region of total shadow. If you were drifting in your spacesuit

in the umbra of Earth's shadow, the sun would be completely hidden behind Earth, and you would not be able to see any part of the sun's bright disk. If you drifted into the **penumbra**, however, you would see part of the sun peeking around the edge of Earth, so you would be in partial shadow. In the penumbra, sunlight is dimmed but not extinguished.

The umbra of Earth's shadow is over three times longer than the distance to the moon and points directly away from the sun. A giant screen placed in the shadow at the average distance of the moon would reveal a dark umbral shadow about 2.5 times the diameter of the moon. The faint outer edges of the penumbra would mark a circle about 4.6 times the diameter of the moon. Consequently, when the moon's orbit carries it through the umbra, it has plenty of room to become completely immersed in shadow.

Total Lunar Eclipses

Once or twice a year, the orbit of the moon carries it through the umbra of Earth's shadow; and, if no part of the moon remains outside the umbra in the partial sunlight of the penumbra, you

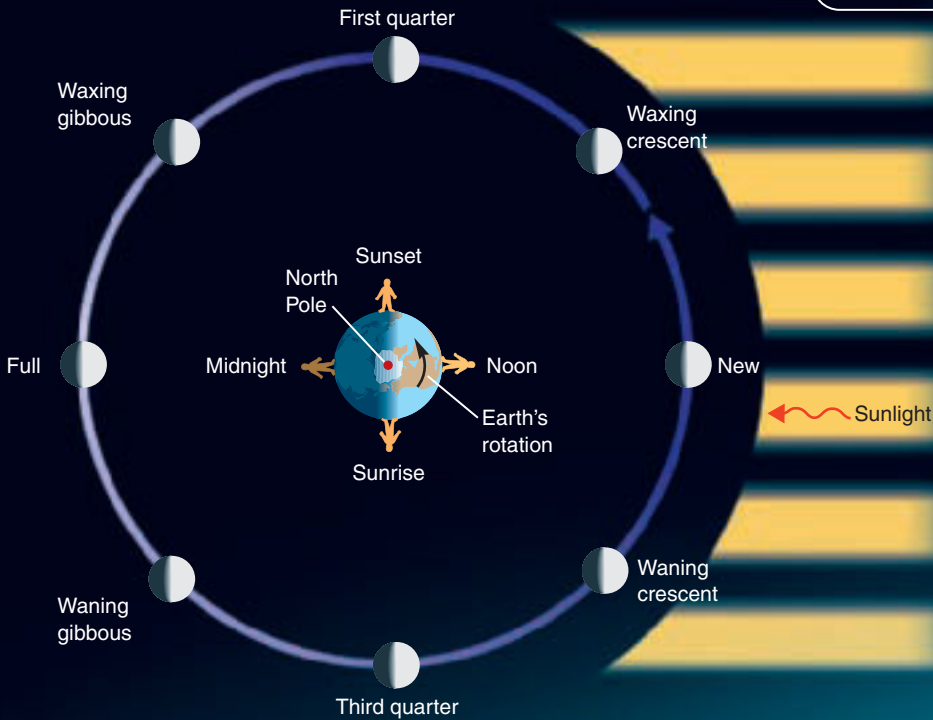
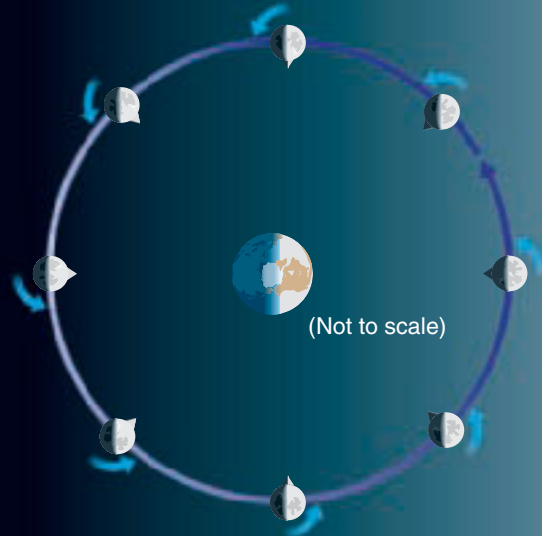


■ **Figure 3-2**

The shadows cast by a map tack resemble the shadows of Earth and the moon. The umbra is the region of total shadow; the penumbra is the region of partial shadow.

The Phases of the Moon

1 As the moon orbits Earth, it rotates to keep the same side facing Earth as shown at right. Consequently you always see the same features on the moon, and you never see the far side of the moon. A mountain on the moon that points at Earth will always point at Earth as the moon revolves and rotates.

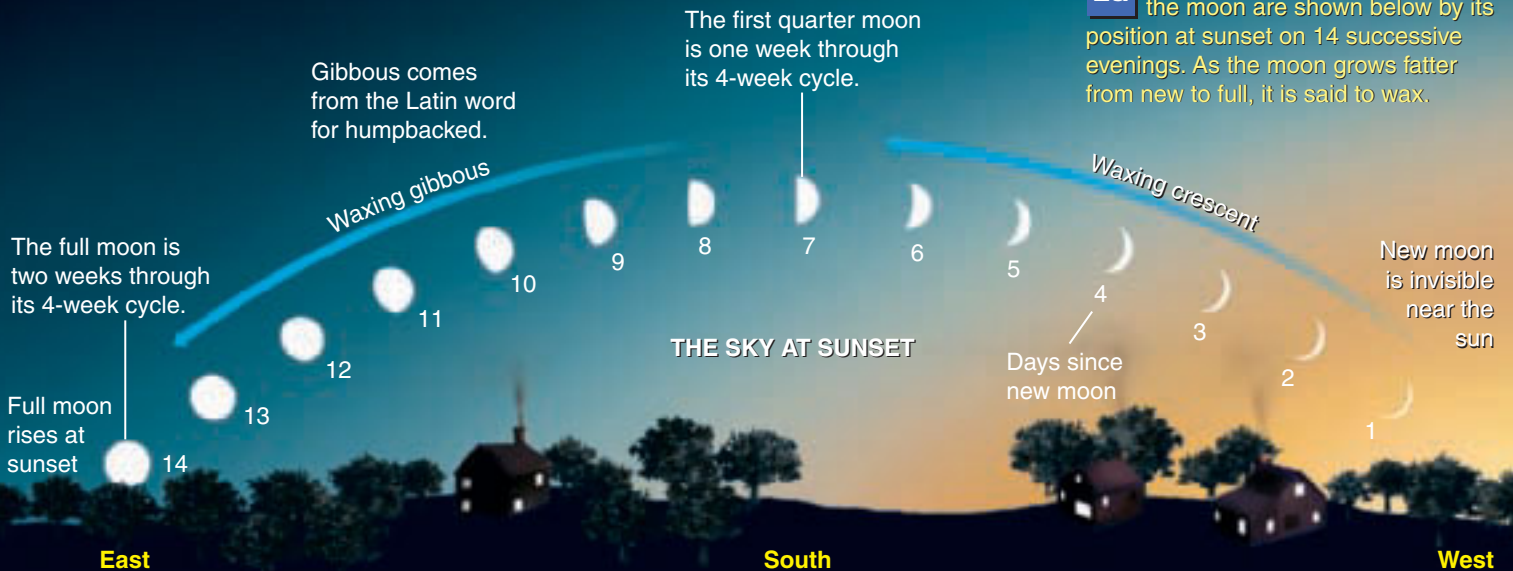


2 As seen at left, sunlight always illuminates half of the moon. Because you see different amounts of this sunlit side, you see the moon cycle through phases. At the phase called "new moon," sunlight illuminates the far side of the moon, and the side you see is in darkness. At new moon you see no moon at all. At full moon, the side you see is fully lit, and the far side is in darkness. How much you see depends on where the moon is in its orbit.

Notice that there is no such thing as the "dark side of the moon." All parts of the moon experience day and night in a month-long cycle.

In the diagram at the left, you see that the new moon is close to the sun in the sky, and the full moon is opposite the sun. The time of day depends on the observer's location on Earth.

2a The first 2 weeks of the cycle of the moon are shown below by its position at sunset on 14 successive evenings. As the moon grows fatter from new to full, it is said to wax.

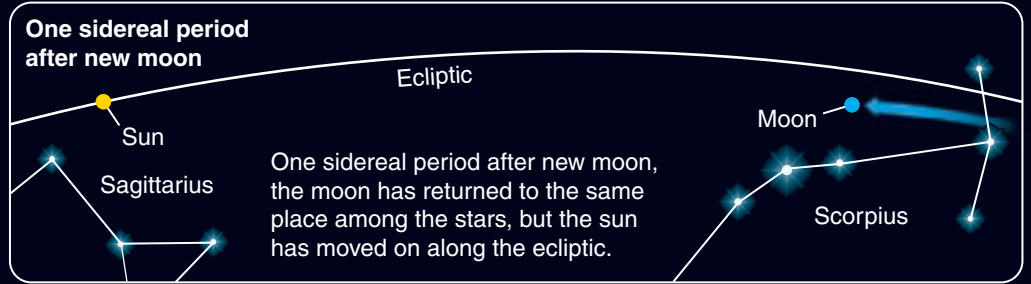


3 The moon orbits eastward around Earth in 27.32 days, its **sidereal period**. This is how long the moon takes to circle the sky once and return to the same position among the stars.

A complete cycle of lunar phases takes 29.53 days, the moon's **synodic period**. (Synodic comes from the Greek words for "together" and "path.")

To see why the synodic period is longer than the sidereal period, study the star charts at the right.

Although you think of the lunar cycle as being about 4 weeks long, it is actually 1.53 days longer than 4 weeks. The calendar divides the year into 30-day periods called months (literally "moonths") in recognition of the 29.53 day synodic cycle of the moon.

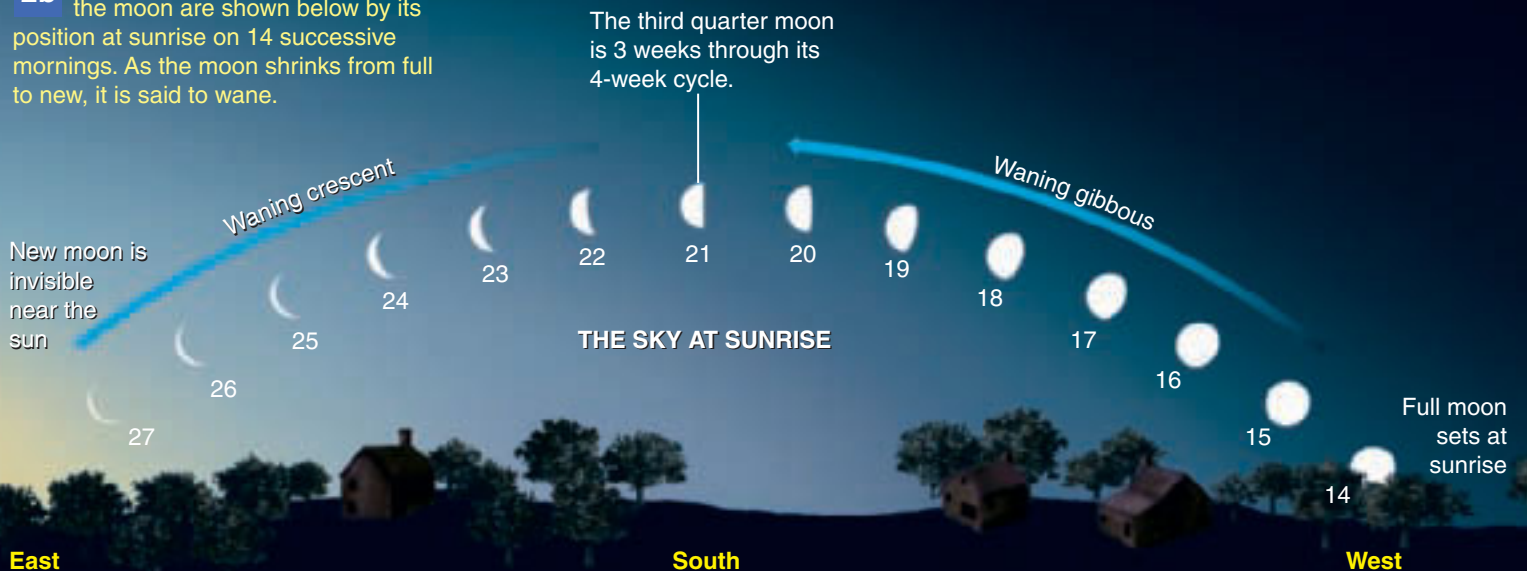


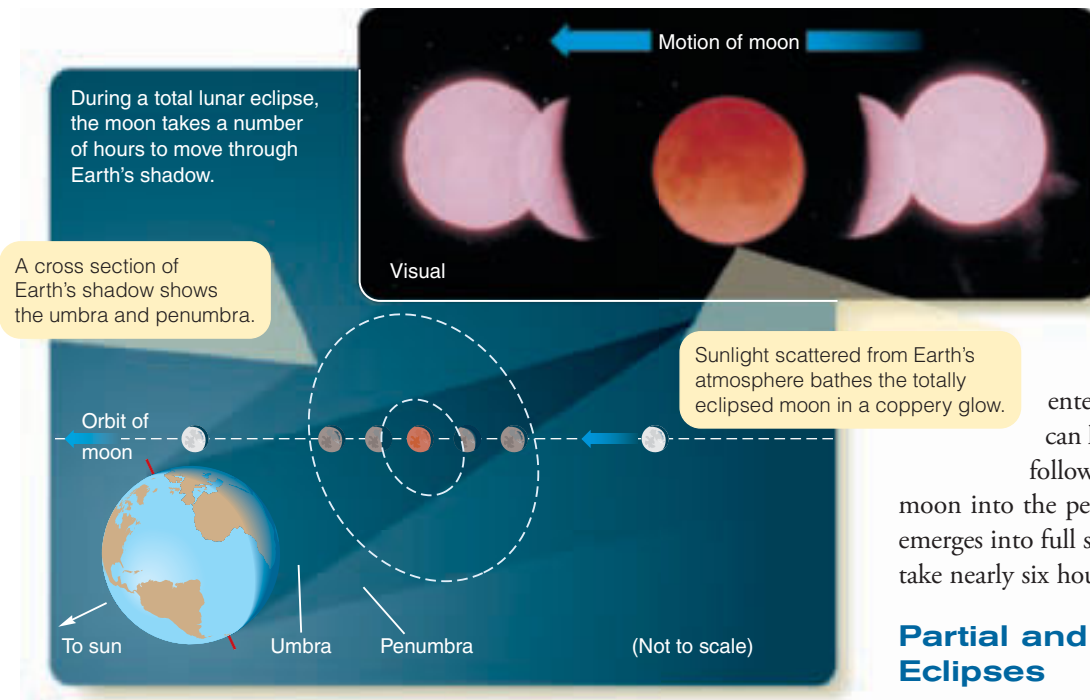
You can use the diagram on the opposite page to determine when the moon rises and sets at different phases.

TIMES OF MOONRISE AND MOONSET

Phase	Moonrise	Moonset
New	Dawn	Sunset
First quarter	Noon	Midnight
Full	Sunset	Dawn
Third quarter	Midnight	Noon

2b The last two weeks of the cycle of the moon are shown below by its position at sunrise on 14 successive mornings. As the moon shrinks from full to new, it is said to wane.





■ **Figure 3-3**

In this diagram of a total lunar eclipse, the moon passes from right to left through Earth's shadow. A multiple-exposure photograph shows the moon passing through the umbra of Earth's shadow. A longer exposure was used to record the moon while it was totally eclipsed. The moon's path appears curved in the photo because of photographic effects. (© 1982 Dr. Jack B. Marling)

see a **total lunar eclipse** (■ Figure 3-3). As you watch the eclipse begin, the moon first moves into the penumbra and dims slightly; the deeper it moves into the penumbra, the more it dims. Eventually, the moon reaches the umbra, and you see the umbral shadow first darken part, then all, of the moon.

When the moon is totally eclipsed, it does not disappear completely. Although it receives no direct sunlight, the moon in the umbra does receive some sunlight that is refracted (bent) through Earth's atmosphere. If you were on the moon during **totality**, you would not see any part of the sun because it would be entirely hidden behind Earth. However, you would see Earth's atmosphere illuminated from behind by the sun. The red glow from this ring of "sunsets" and "sunrises" illuminates the moon during totality and makes it glow coppery red, as shown in ■ Figure 3-4.

How dim the totally eclipsed moon becomes depends on a number of things. If Earth's atmosphere is especially cloudy in the regions that would bend light into the umbra, the moon will be darker than usual. An unusual amount of dust in Earth's atmosphere (from volcanic eruptions, for instance) also causes a dark eclipse. Also, total lunar eclipses tend to be darkest when the moon's orbit carries it through the center of the umbra.

The exact timing of a lunar eclipse depends on where the moon crosses Earth's shadow. If it crosses through the center of the umbra, the eclipse will have maximum length. For such an eclipse, the moon spends about an hour crossing the penumbra and then another hour

entering the darker umbra. Totality can last as long as 1 hour 45 minutes, followed by the emergence of the moon into the penumbra, plus another hour as it emerges into full sunlight. A total lunar eclipse can take nearly six hours from start to finish.

Partial and Penumbral Lunar Eclipses

Because the moon's orbit is inclined by a bit over 5° to the plane of Earth's orbit, the moon does not always pass through the center of the umbra. If the moon passes a bit too far north or south, it may only partially enter the umbra, and you see a **partial lunar eclipse**. The part of the moon that



■ **Figure 3-4**

During a total lunar eclipse, the moon turns coppery red. In this photo, the moon is darkest toward the lower right, the direction toward the center of the umbra. The edge of the moon at upper left is brighter because it is near the edge of the umbra. (Celestron International)

■ **Table 3-1** | **Total and Partial Eclipses of the Moon, 2010 to 2017***

Year	Time** of Mid-eclipse (GMT)	Length of Totality (Hr: Min)	Length of Eclipse† (Hr: Min)
2010 June 26	11:40	Partial	2:42
2010 Dec. 21	8:18	1:12	3:28
2011 June 15	20:13	1:40	3:38
2011 Dec. 10	14:33	0:50	3:32
2012 June 4	11:03	Partial	2:08
2013 April 25	20:10	Partial	0:28
2014 April 15	7:48	1:18	3:34
2014 Oct. 8	10:55	0:58	3:18
2015 April 4	12:02	Partial	3:28
2015 Sept. 28	2:48	72	3:30
2017 Aug. 7	18:22	Partial	1:54

*There are no total or partial lunar eclipses during 2016.

**Times are Greenwich Mean Time. Subtract 5 hours for Eastern Standard Time, 6 hours for Central Standard Time, 7 hours for Mountain Standard Time, and 8 hours for Pacific Standard Time. From your time zone, lunar eclipses that occur between sunset and sunrise will be visible, and those at midnight will be best placed.

†Does not include penumbral phase.

remains in the penumbra receives some direct sunlight, and the glare is usually great enough to prevent your seeing the faint coppery glow of the part of the moon in the umbra. Partial eclipses are interesting, but they are not as beautiful as a total lunar eclipse.

If the orbit of the moon carries it far enough north or south of the umbra, the moon may pass through only the penumbra and never reach the umbra. Such **penumbral lunar eclipses** are not dramatic at all. In the partial shadow of the penumbra, the moon is only partially dimmed. Most people glancing at a penumbral eclipse would not notice any difference from a full moon.

Total, partial, or penumbral, lunar eclipses are interesting events in the night sky and are not difficult to observe. When the full moon passes through Earth's shadow, the eclipse is visible from anywhere on Earth's dark side. Consult ■ Table 3-1 to find the next lunar eclipse visible in your part of the world.

SCIENTIFIC ARGUMENT

What would a total lunar eclipse look like if Earth had no atmosphere?

As a way to test and improve their understanding, scientists often experiment with their ideas by changing one thing and trying to imagine what would happen. In this case, the absence of an atmosphere around Earth would mean that no sunlight would be bent toward the eclipsed moon, and it would not glow red. It would be very dark in the sky during totality.

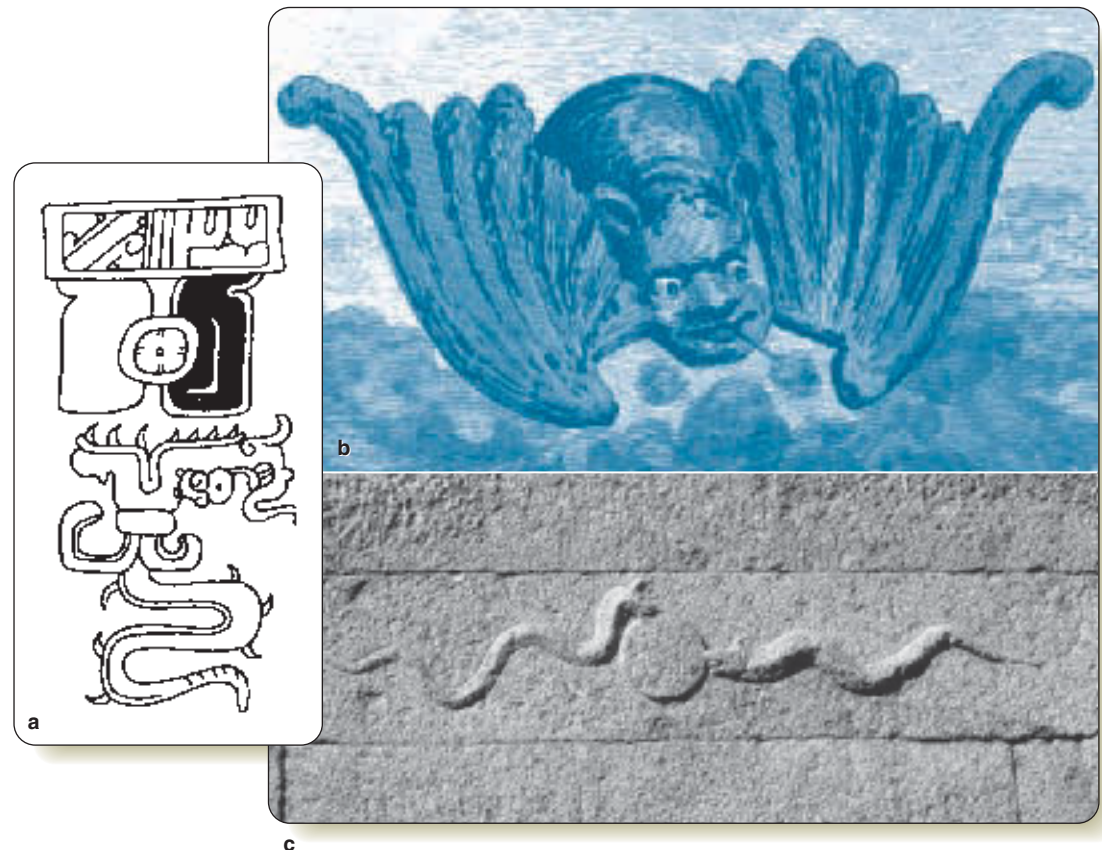
Now change a different parameter. **What would a lunar eclipse look like if the moon and Earth were the same diameter?**

3-3 Solar Eclipses

FOR MILLENNIA, cultures worldwide have understood that the sun is the source of life, so you can imagine the panic people felt at the fearsome sight of the sun gradually disappearing in the middle of the day. Many imagined that the sun was being devoured by a monster (■ Figure 3-5). Modern scientists must

■ **Figure 3-5**

(a) A 12th-century Mayan symbol believed to represent a solar eclipse. The black-and-white sun symbol hangs from a rectangular sky symbol, and a voracious serpent approaches from below. (b) The Chinese representation of a solar eclipse shows a monster usually described as a dragon flying in front of the sun. (From the collection of Yerkes Observatory) (c) This wall carving from the ruins of a temple in Vijayanagara in southern India symbolizes a solar eclipse as two snakes approach the disk of the sun. (T. Scott Smith)



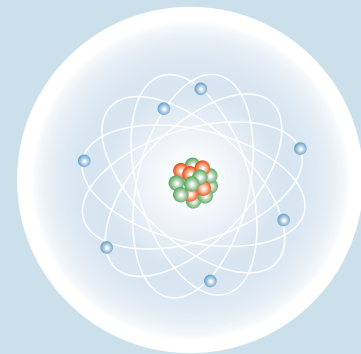
Scientific Imagination

How do scientists produce theories to test? Good scientists are invariably creative people with strong imaginations who can look at raw data about some invisible aspect of nature such as an atom and construct mental pictures as diverse as a plum pudding or a solar system. These scientists share the same human impulse to understand nature that drove ancient cultures to imagine eclipses as serpents devouring the sun.

As the 20th century began, physicists were busy trying to imagine what an atom was like. No one can see an atom, but English physicist J. J. Thomson used what he knew from his experiments and his powerful imagination to create an image of what an atom might be like. He suggested that an atom was a ball of positively charged material with negatively charged electrons distributed throughout like plums in a plum pudding.

The key difference between using a plum pudding to represent the atom and a hungry serpent to represent an eclipse is that the plum pudding model was based on experimental data and could be tested against new evidence. As it turned out, Thomson's student, Ernest Rutherford, performed ingenious new experiments and showed that atoms can't be made like plum puddings. Rather, he imagined an atom as a tiny positively charged nucleus surrounded by negatively charged electrons much like a tiny solar system with planets circling the sun. Later experiments confirmed that Rutherford's description of atoms is closer to reality, and it has become a universally recognized symbol for atomic energy.

Ancient cultures pictured the sun being devoured by a serpent. Thomson, Rutherford, and scientists like them used their scientific imaginations to visualize natural processes and



A model image of the atom as electrons orbiting a small nucleus has become the symbol for atomic energy.

then test and refine their ideas with new experiments and observations. The critical difference is that scientific imagination is continually tested against reality and is revised when necessary.

use their imaginations to visualize how nature works, but with a key difference; they test their ideas against reality (**How Do We Know? 3-1**). You can take comfort that today's astronomers explain solar eclipses without imagining celestial monsters.

A **solar eclipse** occurs when the moon moves between Earth and the sun. If the moon covers the disk of the sun completely, you see a spectacular **total solar eclipse** (■Figure 3-6). If, from your location, the moon covers only part of the sun, you see a less dramatic **partial solar eclipse**. During a solar eclipse, people in one place on Earth may see a total eclipse while people only a few hundred kilometers away see a partial eclipse.

The geometry of a solar eclipse is quite different from that of a lunar eclipse. You can begin by considering how big the sun and moon look in the sky.

The Angular Diameter of the Sun and Moon

Solar eclipses are spectacular because Earth's moon happens to have nearly the same angular diameter as the sun, so it can cover the sun's disk almost exactly. You learned about angular diameter in Chapter 2; now you need to think carefully about how the size and distance of an object like the moon determine its angular diameter.

■ Figure 3-6

Solar eclipses are dramatic. In June 2001, an automatic camera in southern Africa snapped pictures every 5 minutes as the afternoon sun sank lower in the sky. From upper right to lower left, you can see the moon crossing the disk of the sun. A longer exposure was needed to record the total phase of the eclipse. (©2001 F. Espenak)



Visual wavelength images

Linear diameter is simply the distance between an object's opposite sides. You use linear diameter when you order a 16-inch pizza—the pizza is 16 inches across. The linear diameter of the moon is 3476 km.

The angular diameter of an object is the angle formed by lines extending toward you from opposite edges of the object and meeting at your eye (■ Figure 3-7). Clearly, the farther away an object is, the smaller its angular diameter.

To find the angular diameter of the moon, you need to use the **small-angle formula**. It gives you a way to figure out the angular diameter of any object, whether it is a pizza or the moon. In the small-angle formula, you should always express angular diameter in arc seconds and always use the same units for distance and linear diameter:

$$\frac{\text{angular diameter}}{206,265} = \frac{\text{linear diameter}}{\text{distance}}$$

You can use this formula* to find any one of these three quantities if you know the other two; in this case, you are interested in finding the angular diameter of the moon.

The moon has a linear diameter of 3476 km and a distance from Earth of about 384,000 km. Because the moon's linear diameter and distance are both given in the same units, kilometers, you can put them directly into the small-angle formula:

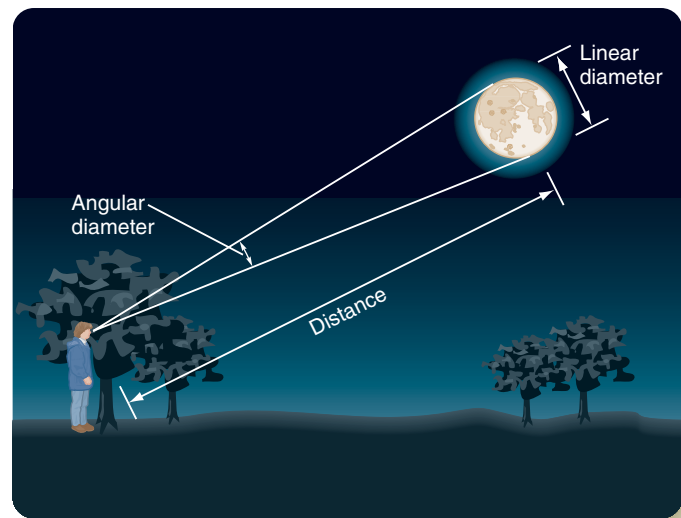
$$\frac{\text{angular diameter}}{206,265} = \frac{3476 \text{ km}}{384,000 \text{ km}}$$

To solve for angular diameter, multiply both sides by 206,265. You will find that the angular diameter of the moon is 1870 arc seconds. If you divide by 60, you get 31 arc minutes, or, dividing by 60 again, about 0.5°. The moon's orbit is slightly elliptical, so the moon can sometimes look a bit larger or smaller, but its angular diameter is always close to 0.5°. It is a **Common Misconception** that the moon is larger when it is on the horizon. Certainly the rising full moon looks big when you see it on the horizon, but that is an optical illusion. In reality, the moon is the same size on the horizon as when it is high overhead.

Now repeat this small-angle calculation to find the angular diameter of the sun. The sun is 1.39×10^6 km in linear diameter and 1.50×10^8 km from Earth. If you put these numbers into the small-angle formula, you will discover that the sun has an angular diameter of 1900 arc seconds, which is 32 arc minutes, or about 0.5°. Earth's orbit is slightly elliptical, and consequently the sun can sometimes look slightly larger or smaller in the sky, but it, like the moon, is always close to 0.5° in angular diameter.

By fantastic good luck, you live on a planet with a moon that is almost exactly the same angular diameter as your sun. Thanks to that coincidence, when the moon passes in front of the sun, it is almost exactly the right size to cover the sun's brilliant surface but leave the sun's atmosphere visible.

*The number 206,265 is the number of arc seconds in a radian. When you divide by 206,265, you convert the angle from arc seconds to radians.



■ **Figure 3-7**

The angular diameter of an object is related to both its linear diameter and its distance.

The Moon's Shadow

To see a solar eclipse, you have to be in the moon's shadow. Like Earth's shadow, the moon's shadow consists of a central umbra of total shadow and a penumbra of partial shadow. The moon's umbral shadow produces a spot of darkness about 270 km (170 mi) in diameter on Earth's surface. (The exact size of the umbral shadow depends on the location of the moon in its elliptical orbit and the angle at which the shadow strikes Earth.) Because of the orbital motion of the moon and the rotation of Earth, the moon's shadow rushes across Earth at speeds of at least 1700 km/h (1060 mph) sweeping out a **path of totality** (■ Figure 3-8). People lucky enough to be in the path of totality will see a total eclipse of the sun when the umbral spot sweeps over them. Observers just outside the path of totality will see a partial solar eclipse as the penumbral shadow sweeps over their location. Those living even farther from the path of totality will see no eclipse.

Sometimes the moon's umbral shadow is not long enough to reach Earth, and, seen from Earth's surface, the disk of the moon is not big enough to cover the sun. The orbit of the moon is slightly elliptical, and its distance from Earth varies. When it is at **apogee**, its farthest point from Earth, its angular diameter is about 6 percent smaller than average, and when it is at **perigee**, its closest point to Earth, its angular diameter is 6 percent larger than average. Another factor is Earth's slightly elliptical orbit around the sun. When Earth is closest to the sun in January, the sun looks 1.7 percent larger in angular diameter; and, when Earth is at its farthest point in July, the sun looks 1.7 percent smaller. If the moon crosses in front of the sun when the moon's disk is smaller in angular diameter than the sun's, it produces an **annular eclipse**, a solar eclipse in which a ring (or annulus) of light is visible around the disk of the moon (■ Figure 3-9). An annular eclipse swept across the United States on May 10, 1994.

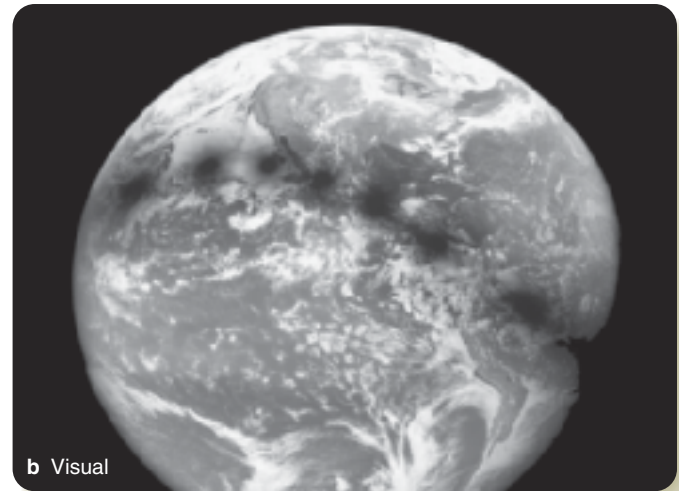
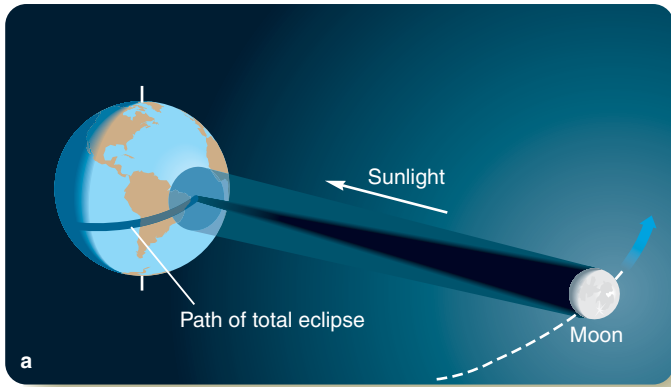
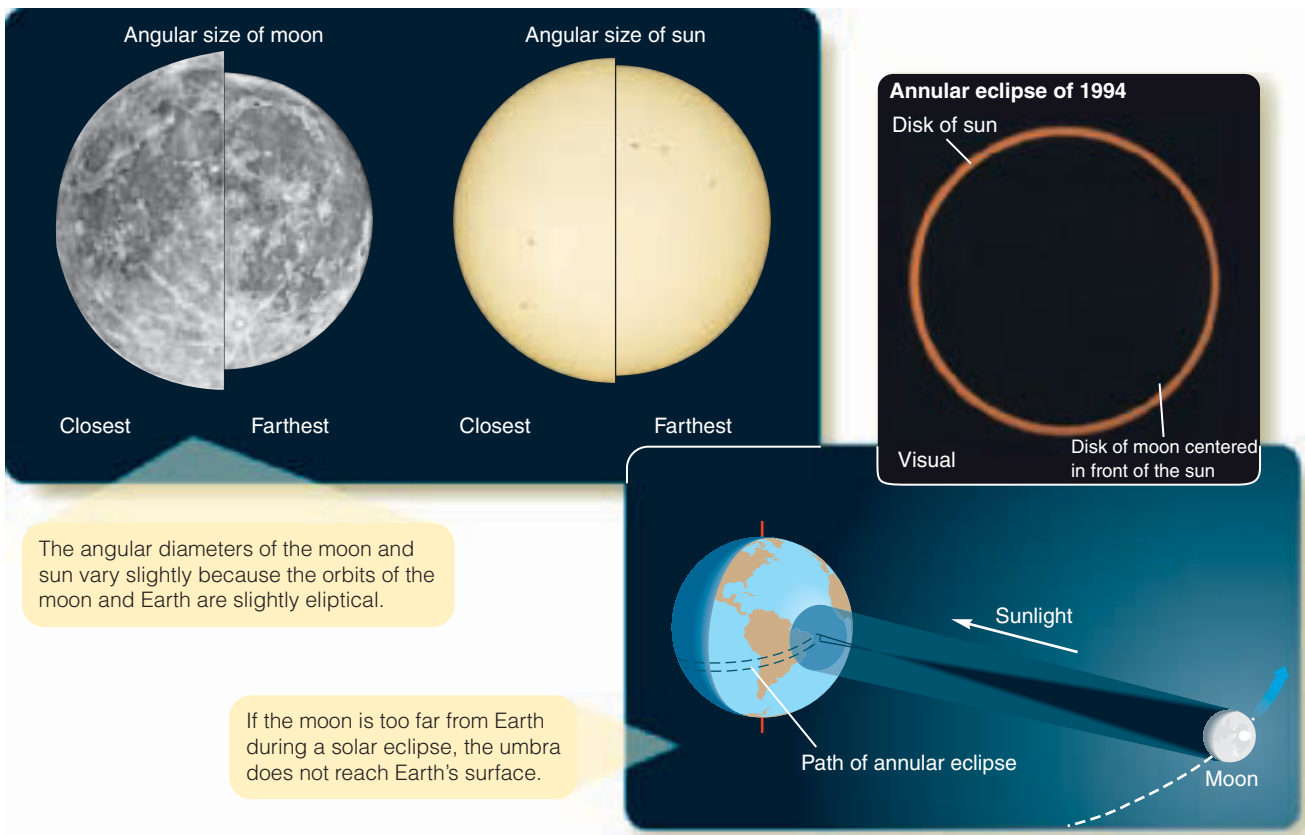


Figure 3-8

(a) The umbra of the moon's shadow sweeps from west to east across Earth, and observers in the path of totality see a total solar eclipse. Those outside the umbra but inside the penumbra see a partial eclipse. (b) Eight photos made by a weather satellite have been combined to show the moon's shadow moving across Mexico, Central America, and Brazil. (NASA GOES images courtesy of MrEclipse.com)



The angular diameters of the moon and sun vary slightly because the orbits of the moon and Earth are slightly elliptical.

If the moon is too far from Earth during a solar eclipse, the umbra does not reach Earth's surface.

Figure 3-9

Because the angular diameter of the moon and the sun vary slightly, the disk of the moon is sometimes too small to cover the disk of the sun. This means the umbra of the moon does not reach Earth, and the eclipse is annular. From Earth, you see an annular eclipse because the moon's angular diameter is smaller than the angular diameter of the sun. In the photograph of the annular eclipse of 1994, the dark disk of the moon is almost exactly centered on the bright disk of the sun. (Daniel Good)

■ **Table 3-2** | **Total and Annular Eclipses of the Sun, 2010 to 2019***

Date	Total/ Annular (T/A)	Time of Mid-eclipse** (GMT)	Maximum Length of Total or Annular Phase (Min:Sec)	Area of Visibility
2010 Jan. 15	A	7 ^h	11:10	Africa, Indian Ocean
2010 July 11	T	20 ^h	5:20	Pacific, South America
2012 May 20	A	23 ^h	5:46	Japan, North Pacific, western USA
2012 Nov. 13	T	22 ^h	4:02	Australia, South Pacific
2013 May 10	A	0 ^h	6:04	Australia, Pacific
2013 Nov. 3	AT	13 ^h	1:40	Atlantic, Africa
2015 March 20	T	10 ^h	2:47	North Atlantic, Arctic
2016 March 9	T	2 ^h	4:10	Borneo, Pacific
2016 Sept. 1	A	9 ^h	3:06	Atlantic, Africa, Indian Ocean
2017 Feb. 26	A	15 ^h	1:22	S. Pacific, S. America, Africa
2017 Aug. 21	T	18 ^h	2:40	Pacific, USA, Atlantic
2019 July 2	T	19 ^h	4:32	Pacific, South America
2019 Dec. 26	A	5 ^h	3:40	Southeast Asia, Pacific

The next major total solar eclipse visible from the United States will occur on August 21, 2017, when the path of totality will cross the United States from Oregon to South Carolina.

*There are no total or partial solar eclipses in 2011, 2014, or 2018.

**Times are Greenwich Mean Time. Subtract 5 hours for Eastern Standard Time, 6 hours for Central Standard Time, 7 hours for Mountain Standard Time, and 8 hours for Pacific Standard Time.

^h hours.

Total solar eclipses are rare as seen from any one place. If you stay in one location, you will see a total solar eclipse about once in 360 years. Some people are eclipse chasers. They plan years in advance and travel halfway around the world to place themselves in the path of totality. ■ Table 3-2 shows the date and location of solar eclipses over the next few years.

Features of Solar Eclipses

A solar eclipse begins when you first see the edge of the moon encroaching on the sun. This is the moment when the edge of the penumbra sweeps over your location.

During the partial phases of a solar eclipse, the moon gradually covers the bright disk of the sun (■ Figure 3-10). Totality begins as the last sliver of the sun's bright surface disappears behind the moon. This is the moment when the edge of the umbra sweeps over your location. So long as any of the sun is visible, the countryside is bright; but, as the last of the sun disappears, dark falls in a few seconds. Automatic streetlights come on, car drivers switch on their headlights, and birds go to roost. The darkness of totality depends on a number of factors, including the weather at the observing site, but it is usually dark enough to make it difficult to read the settings on cameras.

The totally eclipsed sun is a spectacular sight. With the moon covering the bright surface of the sun, called the **photosphere**,* you can see the sun's faint outer atmosphere, the **corona**, glowing with a pale, white light so faint you can safely look at it directly. The

*The photosphere, corona, chromosphere, and prominences will be discussed in detail in Chapter 8. Here the terms are used as the names of features you see during a total solar eclipse.

corona is made of hot, low-density gas that is given a wispy appearance by the solar magnetic field, as shown in the last frame of Figure 3-10. Also visible just above the photosphere is a thin layer of bright gas called the **chromosphere**. The chromosphere is often marked by eruptions on the solar surface, called **prominences** (■ Figure 3-11a), that glow with a clear, pink color due to the high temperature of the gases involved. The small-angle formula reveals that a large prominence is about 3.5 times the diameter of Earth.

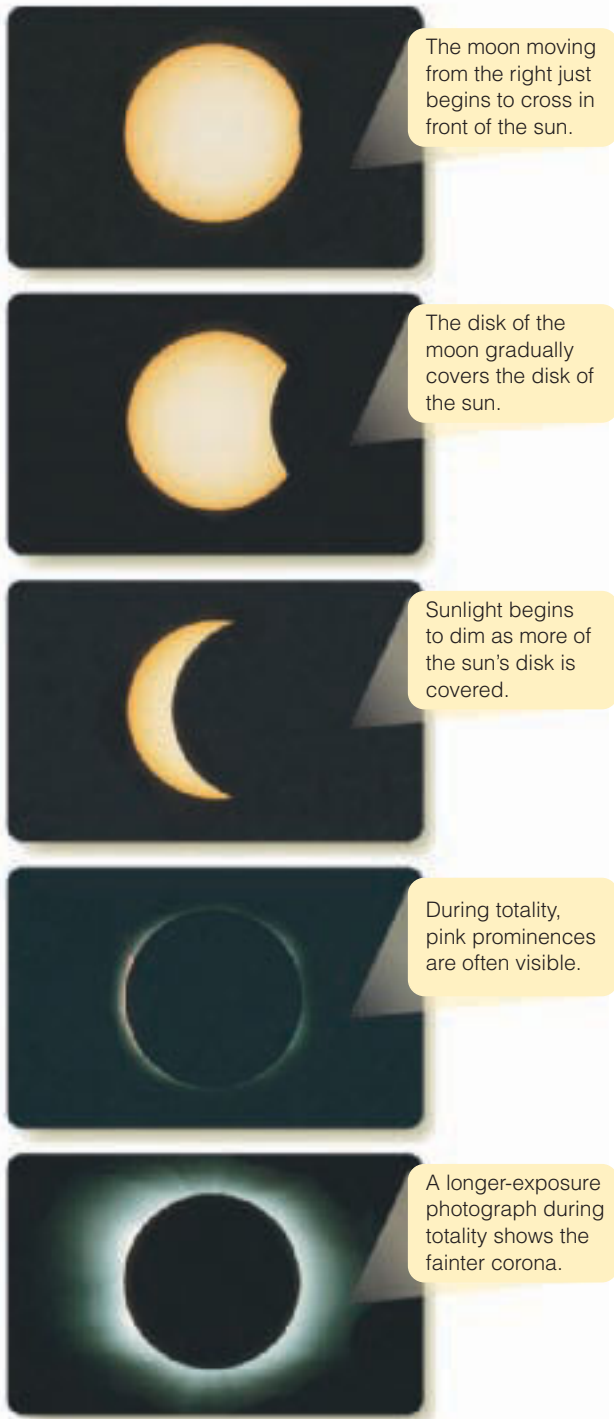
Totality during a solar eclipse cannot last longer than 7.5 minutes under any circumstances, and the average is only 2 to 3 minutes. Totality ends when the sun's bright surface reappears at the trailing edge of the moon. Daylight returns quickly, and the corona and chromosphere vanish. This corresponds to the moment when the trailing edge of the moon's umbra sweeps over the observer.

Just as totality begins or ends, a small part of the photosphere can peek through a valley at the edge of the lunar disk. Although it is intensely bright, such a small part of the photosphere does not completely drown out the fainter corona, which forms a silvery ring of light with the brilliant spot of photosphere gleaming like a diamond (■ Figure 3-11b). This **diamond ring effect** is one of the most spectacular of astronomical sights, but it is not visible during every solar eclipse. Its occurrence depends on the exact orientation and motion of the moon.

Observing an Eclipse

Not too many years ago, astronomers traveled great distances to forbidding places to get their instruments into the path of totality so they could study the faint outer corona that is visible only during the few minutes of a total solar eclipse. Now, many of those observations can be made every day by solar telescopes in

A Total Solar Eclipse

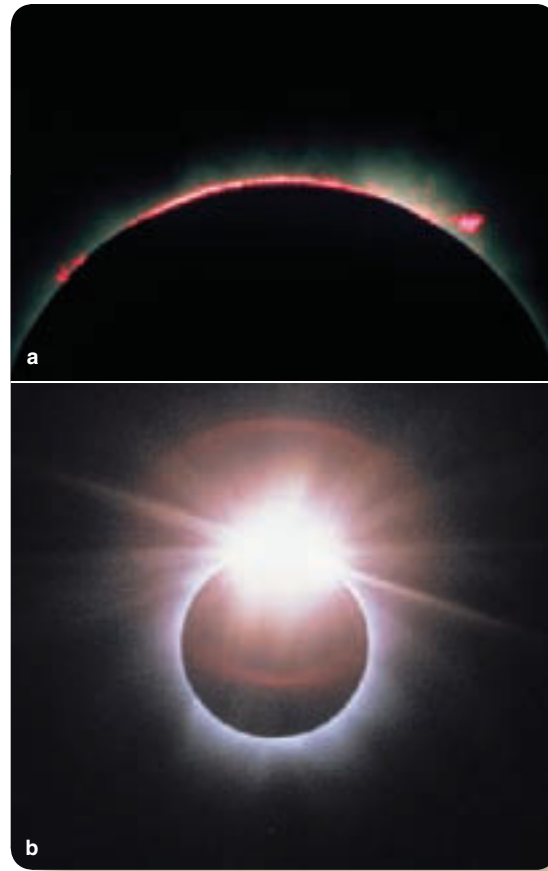


■ **Figure 3-10**

This sequence of photos shows the first half of a total solar eclipse. (Daniel Good)

space, but eclipse enthusiasts still journey to exotic places for the thrill of seeing a total solar eclipse.

No matter how thrilling a solar eclipse is, you must be cautious when viewing it. During the partial phase, part of the sun remains visible, so it is hazardous to look at the eclipse without protection.



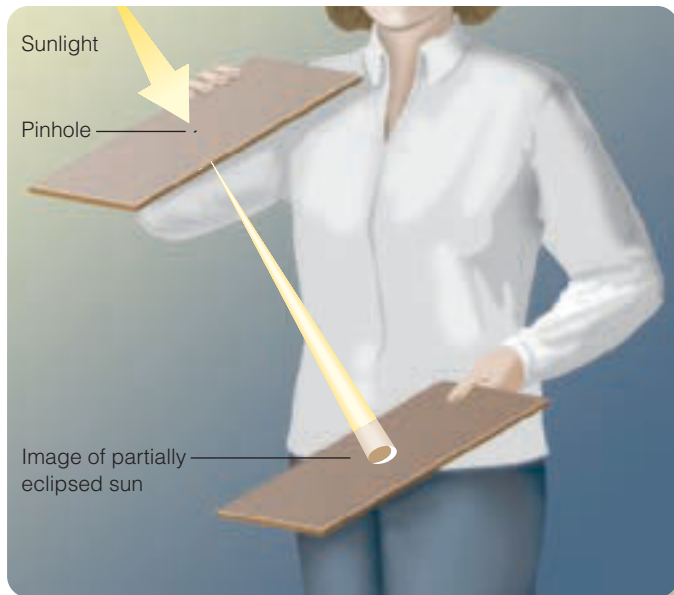
■ **Figure 3-11**

(a) During a total solar eclipse, the moon covers the photosphere, and the ruby-red chromosphere and prominences are visible. Only the lower corona is visible in this image. (©2005 by Fred Espenak) (b) The diamond ring effect can sometimes occur momentarily at the beginning or end of totality if a small segment of the photosphere peeks out through a valley at the edge of the lunar disk. (National Optical Astronomy Observatory)

Dense filters and exposed film do not necessarily provide protection because some filters do not block the invisible heat radiation (infrared) that can burn the retina of your eyes. Dangers like these have led officials to warn the public not to look at solar eclipses at all and have even frightened some people into locking themselves and their children into windowless rooms. It is a **Common Misconception** that sunlight is somehow more dangerous during an eclipse. In fact, it is always dangerous to look at the sun. The danger posed by an eclipse is that people are tempted to ignore common sense and look at the sun directly, which can burn their eyes.

The safest and simplest way to observe the partial phases of a solar eclipse is to use pinhole projection. Poke a small pinhole in a sheet of cardboard. Hold the sheet with the hole in sunlight and allow light to pass through the hole and onto a second sheet of cardboard (■ Figure 3-12). On a day when there is no eclipse, the result is a small, round spot of light that is an image of the sun. During the partial phases of a solar eclipse, the image will show the dark silhouette of the moon obscuring part of the sun. Pinhole

3-4 Predicting Eclipses



■ **Figure 3-12**

A safe way to view the partial phases of a solar eclipse. Use a pinhole in a card to project an image of the sun on a second card. The greater the distance between the cards, the larger (and fainter) the image will be.

images of the partially eclipsed sun can also be seen in the shadows of trees as sunlight peeks through the tiny openings between the leaves and branches. This can produce an eerie effect just before totality as the remaining sliver of sun produces thin crescents of light on the ground under trees. Once totality begins, it is safe to look directly. The totally eclipsed sun is fainter than the full moon.

SCIENTIFIC ARGUMENT

If you were on Earth watching a total solar eclipse, what would astronauts on the moon see when they looked at Earth?

Building this argument requires that you change your point of view and imagine seeing the eclipse from a new location. Scientists commonly imagine seeing events from multiple points of view as a way to develop and test their understanding. Astronauts on the moon could see Earth only if they were on the side that faces Earth. Because solar eclipses always happen at new moon, the near side of the moon would be in darkness, and the far side of the moon would be in full sunlight. The astronauts on the near side of the moon would be standing in darkness, and they would be looking at the fully illuminated side of Earth. They would see Earth at full phase. The moon's shadow would be crossing Earth; and, if the astronauts looked closely, they might be able to see the spot of darkness where the moon's umbral shadow touched Earth. It would take hours for the shadow to cross Earth.

Standing on the moon and watching the moon's umbral shadow sweep across Earth would be a cold, tedious assignment. Perhaps you can imagine a more interesting assignment for the astronauts.

What would astronauts on the moon see while people on Earth were seeing a total lunar eclipse?

A CHINESE STORY TELLS of two astronomers, Hsi and Ho, who were too drunk to predict the solar eclipse of October 22, 2137 BC. Or perhaps they failed to conduct the proper ceremonies to scare away the dragon that, according to Chinese tradition, was snacking on the sun's disk. When the emperor recovered from the terror of the eclipse, he had the two astronomers beheaded.

Making exact eclipse predictions requires a computer and proper software, but some ancient astronomers could make educated guesses as to which full moons and which new moons might result in eclipses. There are three good reasons to reproduce their methods. First, it is an important chapter in the history of science. Second, it will illustrate how apparently complex phenomena can be analyzed in terms of cycles. Third, eclipse prediction will exercise your scientific imagination and help you visualize Earth, the moon, and the sun as objects moving through space.

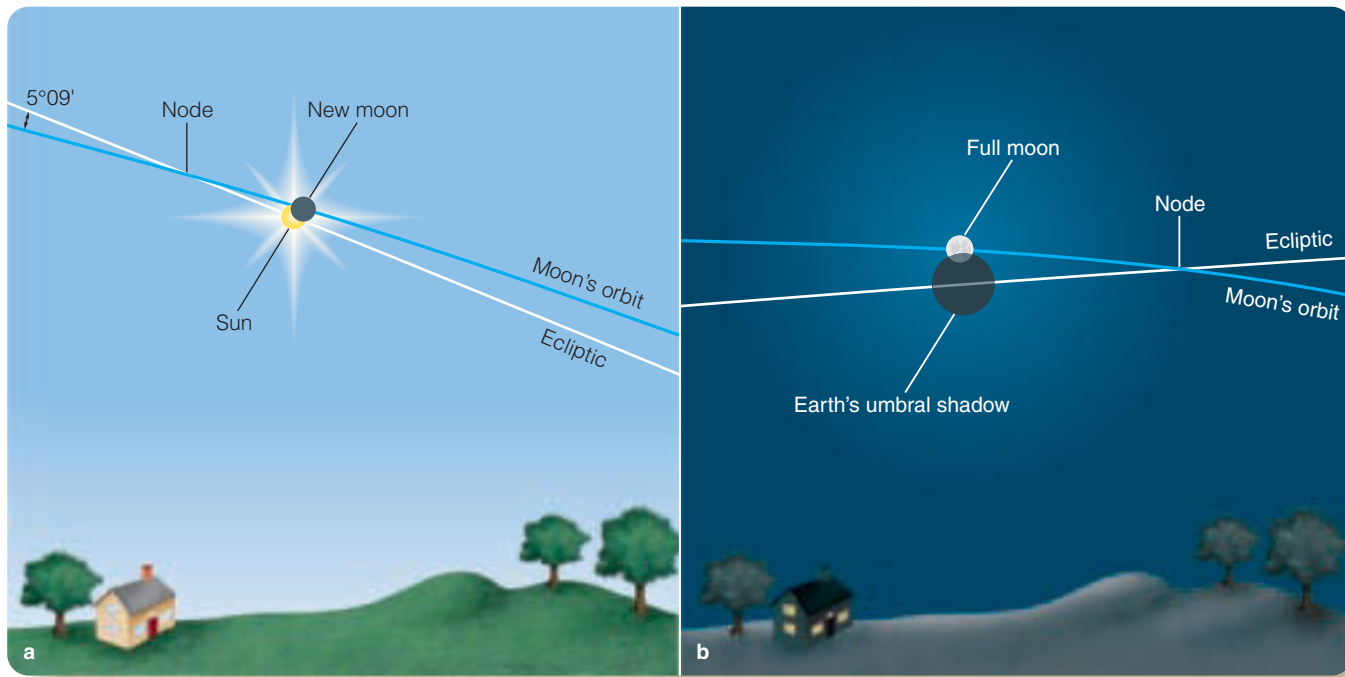
Conditions for an Eclipse

You can predict eclipses by thinking about the motion of the sun and moon in the sky. Imagine that you can look up into the sky from your home on Earth and see the sun moving along the ecliptic and the moon moving along its orbit. Because the orbit of the moon is tipped slightly over 5 degrees to the plane of Earth's orbit, you see the moon follow a path tipped by the same angle to the ecliptic. Each month, the moon crosses the ecliptic at two points called **nodes**. It crosses at one node going southward, and two weeks later it crosses at the other node going northward.

Eclipses can only occur when the sun is near one of the nodes of the moon's orbit. Only then can the new moon cross in front of the sun and produce a solar eclipse, as shown in ■ Figure 3-13a. Most new moons pass too far north or too far south of the sun to cause an eclipse. When the sun is near one node, Earth's shadow points near the other node, and a full moon can enter the shadow and be eclipsed. A lunar eclipse doesn't happen at every full moon because most full moons pass too far north or too far south of the ecliptic and miss Earth's shadow. You can see a partial lunar eclipse illustrated in ■ Figure 3-13b.

So, there are two conditions for an eclipse: The sun must be near a node, and the moon must be crossing either the same node (solar eclipse) or the other node (lunar eclipse). That means, of course, that solar eclipses can occur only when the moon is new, and lunar eclipses can occur only when the moon is full.

Now you know the ancient secret of predicting eclipses. An eclipse can occur only in a period called an **eclipse season**, during which the sun is close to a node in the moon's orbit. For solar eclipses, an eclipse season is about 32 days long. Any new moon during this period will produce a solar eclipse. For lunar eclipses, the eclipse season is a bit shorter, about 22 days. Any full moon in this period will encounter Earth's shadow and be eclipsed.



■ **Figure 3-13**

Eclipses can occur only when the sun is near one of the nodes of the moon's orbit. (a) A solar eclipse occurs when the moon meets the sun near a node. (b) A lunar eclipse occurs when the sun and moon are near opposite nodes. Partial eclipses are shown here for clarity.

This makes eclipse prediction easy. All you have to do is keep track of where the moon crosses the ecliptic (where the nodes of its orbit are). This system works fairly well, and ancient astronomers such as the Maya may have used such a system. You could have been a very successful ancient Mayan astronomer with what you know about eclipse seasons, but you can do even better if you change your point of view.

The View from Space

Change your point of view and imagine that you are looking at the orbits of Earth and the moon from a point far away in space. You can imagine the moon's orbit tipped at an angle to Earth's orbit. As Earth orbits the sun, the moon's orbit remains fixed in direction. The nodes of the moon's orbit are the points where it passes through the plane of Earth's orbit; an eclipse season occurs each time the line connecting these nodes, the **line of nodes**, points toward the sun. Look at ■ Figure 3-14a and notice that the line of nodes does not point at the sun in the example at lower left, and no eclipses are possible; the shadows miss. At lower right, the line of nodes points toward the sun, and the shadows produce eclipses.

The shadows of Earth and moon are long and thin, as shown in ■ Figure 3-14b. That is why it is so easy for them to miss their mark at new moon or full moon and fail to produce an eclipse. Only during an eclipse season do the long, skinny shadows produce eclipses.

If you watched for years from your point of view in space, you would see the orbit of the moon precess like a hubcap

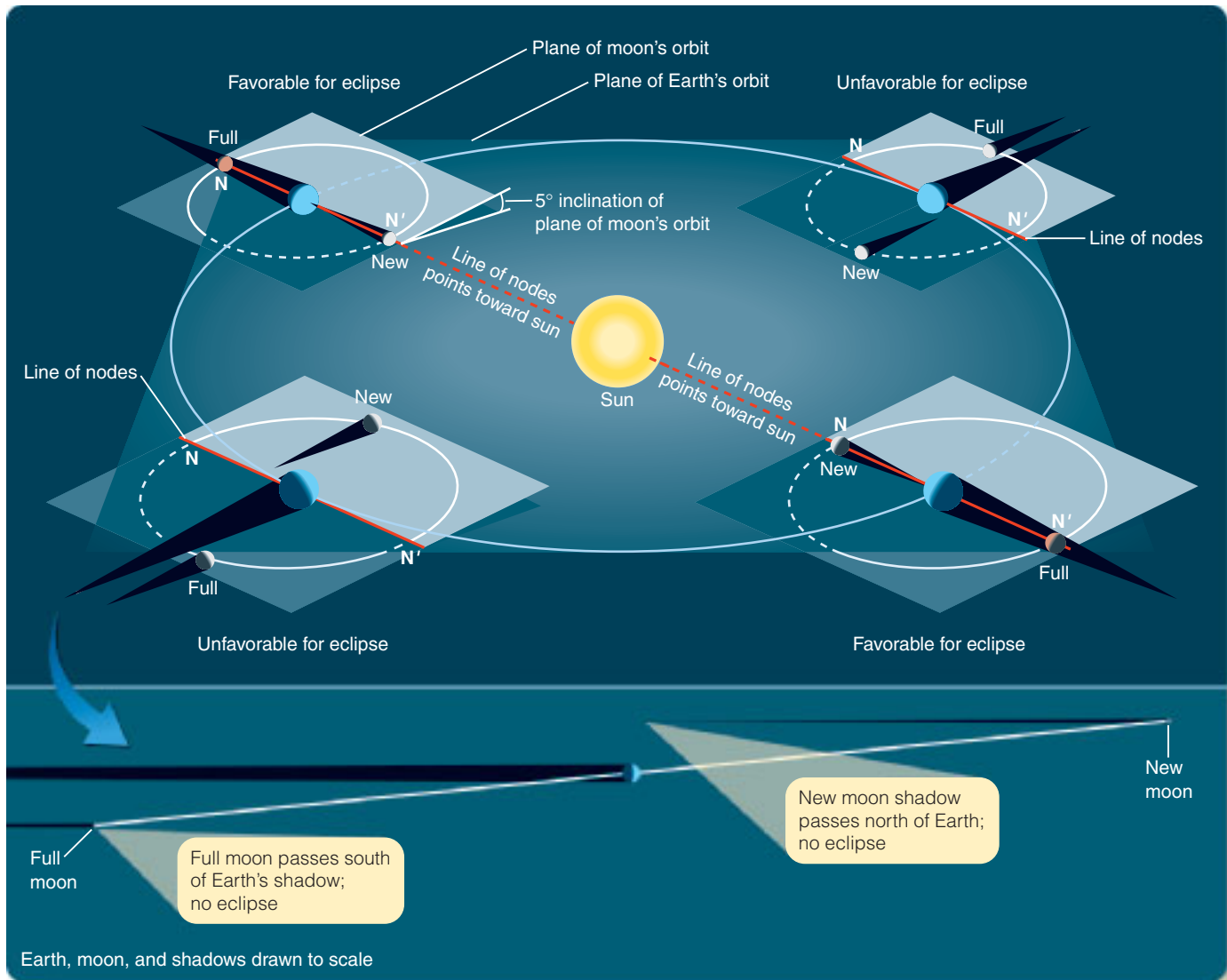
spinning on the ground. This precession is caused mostly by the gravitational influence of the sun, and it makes the line of nodes rotate once every 18.6 years. People back on Earth see the nodes slipping westward along the ecliptic 19.4° per year. Consequently, the sun does not need a full year to go from a node all the way around the ecliptic and back to that same node. Because the node is moving westward to meet the sun, it will cross the node after only 346.6 days (an **eclipse year**). This means that, according to our calendar, the eclipse seasons begin about 19 days earlier every year (■ Figure 3-15). If you see an eclipse in late December one year, you will see eclipses in early December the next year, and so on.

Once you see a few eclipses, you know when the eclipse seasons are occurring, and you can predict next year's eclipse seasons by subtracting 19 days. New moons and full moons near those dates are candidates for causing eclipses.

The cyclic pattern of eclipses shown in Figure 3-15 gives you another way to predict eclipses. Eclipses follow a pattern, and if you were an ancient astronomer and understood the pattern, you could predict eclipses without ever knowing what the moon was or how an orbit works.

The Saros Cycle

Ancient astronomers could predict eclipses in an approximate way using eclipse seasons, but they could have been much more accurate if they had recognized that eclipses occur following certain patterns. The most important of these is the **saros cycle**



■ **Figure 3-14**

The moon's orbit is tipped a bit over 5° to Earth's orbit. The nodes N and N' are the points where the moon passes through the plane of Earth's orbit. If the line of nodes does not point at the sun, the long narrow shadows miss, and there are no eclipses at new moon and full moon. At those parts of Earth's orbit where the line of nodes points toward the sun, eclipses are possible at new moon and full moon.

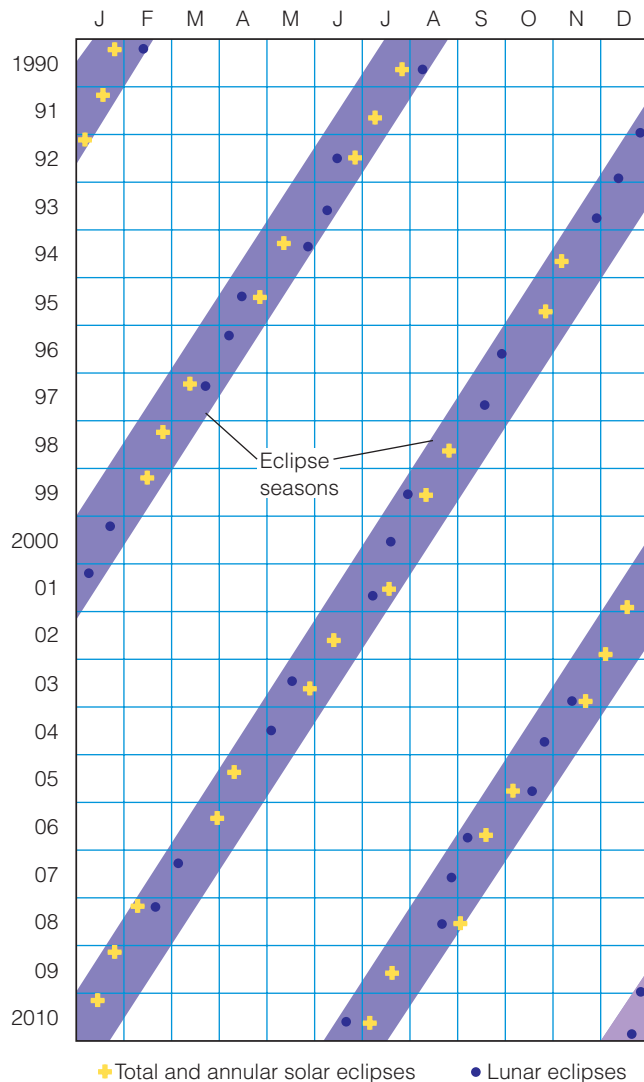
(sometimes referred to simply as the saros). After one saros cycle of 18 years $11\frac{1}{3}$ days, the pattern of eclipses repeats. In fact, *saros* comes from a Greek word that means "repetition."

One saros contains 6585.321 days, which is equal to 223 lunar months. Therefore, after one saros cycle, the moon is back to the same phase it had when the cycle began. But one saros is also equal to 19 eclipse years. After one saros cycle, the sun has returned to the same place it occupied with respect to the nodes of the moon's orbit when the cycle began. If an eclipse occurs on a given day, then 18 years $11\frac{1}{3}$ days later the sun, the moon, and the nodes of the moon's orbit return to nearly the same relationship, and the eclipse occurs all over again.

Although the eclipse repeats almost exactly, it is not visible from the same place on Earth. The saros cycle is one-third of a

day longer than 18 years 11 days. When the eclipse happens again, Earth will have rotated one-third of a turn farther east, and the eclipse will occur one-third of the way westward around Earth (■ Figure 3-16). That means that after three saros cycles—a period of 54 years 1 month—the same eclipse occurs in the same part of Earth.

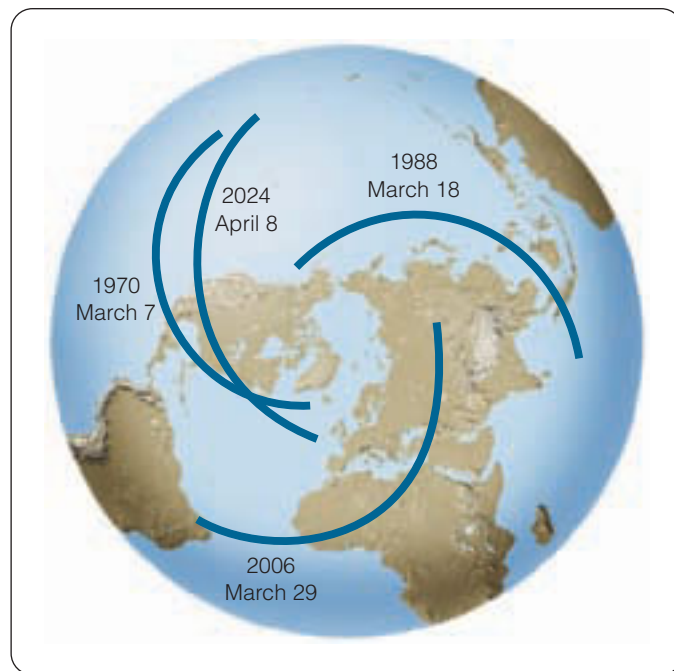
One of the most famous predictors of eclipses was the Greek philosopher Thales of Miletus (about 640–546 BC), who supposedly learned of the saros cycle from the Chaldeans. No one knows which eclipse Thales predicted, but some scholars suspect the eclipse of May 28, 585 BC. In any case, the eclipse occurred at the height of a battle between the Lydians and the Medes, and the mysterious darkness in midafternoon so startled the two armies that they concluded a truce.



■ **Figure 3-15**

A calendar of eclipse seasons. Each year the eclipse seasons begin about 19 days earlier. Any new moon or full moon that occurs during an eclipse season results in an eclipse. Only total and annular eclipses are shown here.

Although there are historical reasons to doubt that Thales actually predicted the eclipse, the important point is that he could have done it. If he had had records of past eclipses of the sun visible from the area, he could have discovered that they tended to recur with a period of 54 years 1 month (three saros cycles). Indeed, he could have predicted the eclipse without ever understanding what the sun and moon were or how they moved.



■ **Figure 3-16**

The saros cycle at work. The total solar eclipse of March 7, 1970, recurred after 18 years $11\frac{1}{3}$ days over the Pacific Ocean. After another interval of 18 years $11\frac{1}{3}$ days, the same eclipse was visible from Asia and Africa. After a similar interval, the eclipse will again be visible from the United States.

SCIENTIFIC ARGUMENT

Why can't two successive full moons be totally eclipsed?

Most people suppose that eclipses occur at random or in some pattern so complex you need a big computer to make predictions. In fact, like many natural events, eclipse prediction can be reduced to a series of simple steps.

A lunar eclipse can happen only when the sun is near one node and the moon crosses Earth's shadow at the other node. A lunar eclipse season is only 22 days long, and any full moon in that time will be eclipsed. However, the moon takes 29.5 days to go from one full moon to the next. If one full moon is totally eclipsed, the next full moon 29.5 days later will occur long after the end of the eclipse season, and there can be no second eclipse.

Now use your knowledge of the cycles of the sun and moon to revise your argument. **How can the sun be eclipsed by two successive new moons?**

What Are We? Scorekeepers

The moon is a companion in our daily lives, in our history, and in our mythology. It makes a dramatic sight as it moves through the sky, cycling through a sequence of phases that has repeated for billions of years. The moon has been humanity's timekeeper. Moses, Jesus, and Muhammad saw the same moon that you see. The moon is part of our human heritage, and famous paintings, poems, plays, and music celebrate the beauty of the moon.

Eclipses of the sun and moon have frightened and fascinated for millennia, and some of humanity's earliest efforts to understand nature were focused on counting the phases of the moon and predicting eclipses. Some astronomers have found evidence that Stonehenge could have been used for eclipse prediction, and the ancient Maya in Central America left behind elaborate tables that allowed them to predict eclipses.

Our lives are ruled by the moon as it divides our year into months, and its cycle from new to first quarter to full to third quarter and back to full divides the month into four weeks. In a Native American story, Coyote gambles with the sun to see if the sun will return after the winter solstice to warm Earth. The moon keeps score. The moon is a symbol of regularity, reliability, and dependability. It is the scorekeeper counting out our weeks and months.

Study and Review

Summary

- ▶ The moon orbits eastward around Earth once a month and rotates on its axis so as to keep the same side facing Earth throughout the month.
- ▶ Because you see the moon by reflected sunlight, its shape appears to change as it orbits Earth and sunlight illuminates different amounts of the side facing Earth.
- ▶ The lunar phases wax from new moon to first quarter to full moon and wane from full moon to third quarter to new moon.
- ▶ A complete cycle of lunar phases takes 29.53 days, which is known as the moon's **synodic period (p. 35)**. The **sidereal period (p. 35)** of the moon—its orbital period with respect to the stars—is a bit over two days shorter.
- ▶ If a full moon passes through Earth's shadow, sunlight is cut off, and the moon darkens in a **lunar eclipse (p. 33)**. If the moon fully enters the dark **umbra (p. 33)** of Earth's shadow, the eclipse is a **total lunar eclipse (p. 36)**; but if it only grazes the umbra, the eclipse is a **partial lunar eclipse (p. 36)**. If the moon enters the partial shadow of the **penumbra (p. 33)** but not the umbra, the eclipse is a **penumbral lunar eclipse (p. 37)**.
- ▶ During **totality (p. 36)**, the eclipsed moon looks copper-red because of sunlight refracted through Earth's atmosphere.
- ▶ The **small-angle formula (p. 39)** allows you to calculate an object's angular diameter from its linear diameter and distance. The angular diameter of the sun and moon is about 0.5 degrees.
- ▶ A **solar eclipse (p. 38)** occurs if a new moon passes between the sun and Earth and the moon's shadow sweeps over Earth's surface along the **path of totality (p. 39)**. Observers inside the path of totality see a **total solar eclipse (p. 38)**, and those just outside the path of totality see a **partial solar eclipse (p. 38)**.
- ▶ When the moon is near **perigee (p. 39)**, the closest point in its orbit, its angular diameter is large enough to cover the sun's photosphere and produce a total eclipse. But if the moon is near **apogee (p. 39)**, the farthest point in its orbit, it looks too small and can't entirely cover the photosphere. A solar eclipse occurring then would be an **annular eclipse (p. 39)**.
- ▶ During a total eclipse of the sun, the bright **photosphere (p. 41)** of the sun is covered, and the fainter **corona (p. 41)**, **chromosphere (p. 41)**, and **prominences (p. 41)** become visible.
- ▶ Sometimes at the beginning or end of the total phase of a total solar eclipse, a small piece of the sun's photosphere can peek out through a valley at the edge of the moon and produce a **diamond ring effect (p. 41)**.
- ▶ Looking at the sun is dangerous and can burn the retinas of your eyes. The safest way to observe the partial phases of a solar eclipse is by pinhole projection. Only during totality, when the photosphere is completely hidden, is it safe to look at the sun directly.
- ▶ Solar eclipses must occur at new moon, and lunar eclipses must occur at full moon. Because the moon's orbit is tipped a few degrees from the plane of Earth's orbit, most new moons cross north or south of the sun, and there are no solar eclipses in those months. Similarly, most full moons cross north or south of Earth's shadow, and there are no lunar eclipses in those months.
- ▶ The moon's orbit crosses the ecliptic at two locations called **nodes (p. 43)**, and eclipses can occur only when the sun is crossing a node. During these periods, called **eclipse seasons (p. 43)**, a new moon will cause a solar eclipse, and a full moon can cause a lunar eclipse. An eclipse season occurs each time the **line of nodes (p. 44)** points toward the sun. Knowing when the eclipse seasons occur would allow you to guess which new moons and full moons could cause eclipses.
- ▶ Because the orbit of the moon precesses, the nodes slip westward along the ecliptic, and it takes the sun only about 347 days to go from a node around the ecliptic and back to the same node. This is called an **eclipse year (p. 44)**.
- ▶ Because the nodes of the moon's orbit move westward, eclipse seasons begin about 19 days earlier each year.
- ▶ Eclipses follow a pattern called the **saros cycle (p. 44)**. After one saros of 18 years $11\frac{1}{3}$ days, the pattern of eclipses repeats. Some ancient astronomers knew of the saros cycle and used it to predict eclipses.

Review Questions

1. Which lunar phases would be visible in the sky at dawn? At midnight?
2. If you looked back at Earth from the moon, what phase would Earth have when the moon was full? New? A first-quarter moon? A waxing crescent?
3. If a planet has a moon, must that moon go through the same phases that Earth's moon displays?
4. Could a solar-powered spacecraft generate any electricity while passing through Earth's umbral shadow? Through Earth's penumbral shadow?
5. If a lunar eclipse occurred at midnight, where in the sky would you look to see it?
6. Why do solar eclipses happen only at new moon? Why not every new moon?
7. Why isn't the corona visible during partial or annular solar eclipses?
8. Why can't the moon be eclipsed when it is halfway between the nodes of its orbit?
9. Why aren't solar eclipses separated by one saros cycle visible from the same location on Earth?
10. How could Thales of Miletus have predicted the date of a solar eclipse without observing the location of the moon in the sky?
11. **How Do We Know?** Some people think science is like a grinder that cranks data into theories. What would you tell them about the need for scientists to be creative and imaginative?

Discussion Questions

1. How would eclipses be different if the moon's orbit were not tipped with respect to the plane of Earth's orbit?
2. Are there other planets in our solar system from whose surface you could see a "lunar" (moon) eclipse? A total solar eclipse? Which ones and why?

Problems

1. Identify the phases of the moon if on March 20 the moon is located at the point on the ecliptic called (a) the vernal equinox, (b) the autumnal equinox, (c) the summer solstice, (d) the winter solstice.
2. Identify the phases of the moon if at sunset the moon is (a) near the eastern horizon, (b) high in the southern sky, (c) in the southeastern sky, (d) in the southwestern sky.
3. About how many days must elapse between first-quarter moon and third-quarter moon?

4. If on March 1 the full moon is near the Favorite Star Spica, when will the moon next be full? When will it next be near Spica?
5. How many times larger than the moon is the diameter of Earth's umbral shadow at the moon's distance? (*Hint:* See the photo in Figure 3-3.)
6. Use the small-angle formula to calculate the angular diameter of Earth as seen from the moon.
7. During solar eclipses, large solar prominences are often seen extending 5 arc minutes from the edge of the sun's disk. How far is this in kilometers? In Earth diameters?
8. If a solar eclipse occurs on October 3: (a) Why can't there be a lunar eclipse on October 13? (b) Why can't there be a solar eclipse on December 28?
9. A total eclipse of the sun was visible from Canada on July 10, 1972. When did eclipse occur next with the same sun-moon-Earth geometry? From what part of Earth was it total?
10. When will the eclipse described in Problem 9 next be total as seen from Canada?
11. When will the eclipse seasons occur during the current year? What eclipse(s) will occur?

Learning to Look

1. Use the photos in Figure 3-1 as evidence to show that the moon always keeps the same side facing Earth.
2. Draw the umbral and penumbral shadows onto the diagram in the middle of page 34. Use the diagram to explain why lunar eclipses can occur only at full moon and solar eclipses can occur only at new moon.
3. Can you detect the saros cycle in Figure 3-15?
4. The stamp at right shows a crescent moon. Explain why the moon could never look this way.
5. The photo at right shows the annular eclipse of May 30, 1984. How is it different from the annular eclipse shown in Figure 3-9?



4

The Origin of Modern Astronomy



Guidepost

The preceding chapters gave you a modern view of Earth. You can now imagine how Earth, the moon, and the sun move through space and how that produces the sights you see in the sky. But how did humanity first realize that we live on a planet moving through space? That required the revolutionary overthrow of an ancient and honored theory of Earth's place.

By the 16th century, many astronomers were uncomfortable with the ancient theory that Earth sat at the center of a spherical universe. In this chapter, you will discover how a Polish astronomer named Nicolaus Copernicus changed the old theory, how a German astronomer named Johannes Kepler discovered the laws of planetary motion, and how the Italian Galileo Galilei changed the way we know about nature. Here you will find answers to four essential questions:

— **How did classical philosophers describe Earth's place in the universe?**

— **How did Copernicus revise that ancient theory?**

— **How did astronomers discover the laws of planetary motion?**

— **Why was Galileo condemned by the Inquisition?**

This chapter is not just about the history of astronomy. As they struggled to understand Earth and the heavens, the astronomers of the Renaissance invented a new way of understanding nature—a way of thinking that is now called science.

Galileo's telescope revealed such things as craters on the moon, and he explained how that evidence could be used to test the prevailing Earth-centered model of the universe. He was condemned by the Inquisition in 1633. (Science magazine [www.science mag.org, 16 January 2009, page 326 [top].)

How you would burst out laughing, my dear Kepler, if you would hear what the greatest philosopher of the Gymnasium told the Grand Duke about me...

— FROM A LETTER BY GALILEO GALILEI

ABOUT FOUR CENTURIES AGO, Galileo was condemned by the Inquisition for his part in a huge controversy over the nature of the universe, a controversy that focused on two problems. The place of the Earth was the most acrimonious issue; was it the center of the universe or was the sun at the center? A related issue was the nature of planetary motion. Ancient astronomers could see the sun, moon, and planets moving along the ecliptic, but they couldn't describe those motions precisely. To solve the first problem of the place of the Earth, astronomers also had to solve the second problem of planetary motion.

4-1 The Roots of Astronomy

ASTRONOMY HAS ITS ORIGIN in a noble human trait, curiosity. Just as modern children ask their parents what the stars are and why the moon changes, so did ancient humans ask themselves those same questions. Their answers, often couched in mythical or religious terms, reveal great reverence for the order of the heavens.

Archaeoastronomy

Most of the history of astronomy is lost forever. You can't go to a library or search the Internet to find out what the first astronomers thought about their world because they left no written record. The study of the astronomy of ancient peoples has been called **archaeoastronomy**, and it clearly shows that trying to understand the heavens is part of human nature.

Perhaps the best-known example of archaeoastronomy is also a huge tourist attraction. Stonehenge, standing on Salisbury Plain in southern England, was built in stages from about 3000 BC to about 1800 BC, a period extending from the late Stone Age into the Bronze Age. Though the public is most familiar with the monument's massive stones, they were added late in its history. In its first stages, Stonehenge consisted of a circular ditch slightly larger in diameter than the length of a football field, with a concentric bank just inside the ditch and a long avenue leading away toward the northeast. A massive stone, the Heelstone, stood then, as it does now, outside the ditch in the opening of the avenue.

As early as AD 1740, the English scholar W. Stukely suggested that the avenue pointed toward the rising sun at the summer solstice, but few historians accepted that it was intentional. Nevertheless, seen from the center of the monument, the summer solstice sun does rise behind the Heelstone. More recently, astronomers have recognized other significant astronomical alignments at Stonehenge. For example, sight lines point toward the most northerly and most southerly risings of the moon (■ Figure 4-1).

The significance of these alignments has been debated. Some have claimed that the Stone Age people who built Stonehenge were using it as a device to predict lunar eclipses. After studying eclipse prediction in the previous chapter, you understand that predicting eclipses is easier than most people assume, so perhaps it was used in that way, but the truth may never be known. The builders of Stonehenge had no written language and left no records of their intentions. Nevertheless, the presence of solar and lunar alignments at Stonehenge and at many other Stone Age monuments dotting England and continental Europe shows that so-called primitive peoples were paying close attention to the sky. The roots of astronomy lie not in sophisticated science and logic but in human curiosity and wonder.

Astronomical alignments in sacred structures are common all around the world. For example, many tombs are oriented toward the rising sun, and Newgrange, a 5000-year-old passage-grave in Ireland (■ Figure 4-2), faces southeast so that, at dawn on the day of the winter solstice, light from the rising sun shines into its long passageway and illuminates the central chamber. No one today knows what the alignment meant to the builders of Newgrange, and many experts doubt that it was actually intended to be a tomb. Whatever its original purpose, Newgrange is clearly a sacred site linked by its alignment to the order and power of the sky.

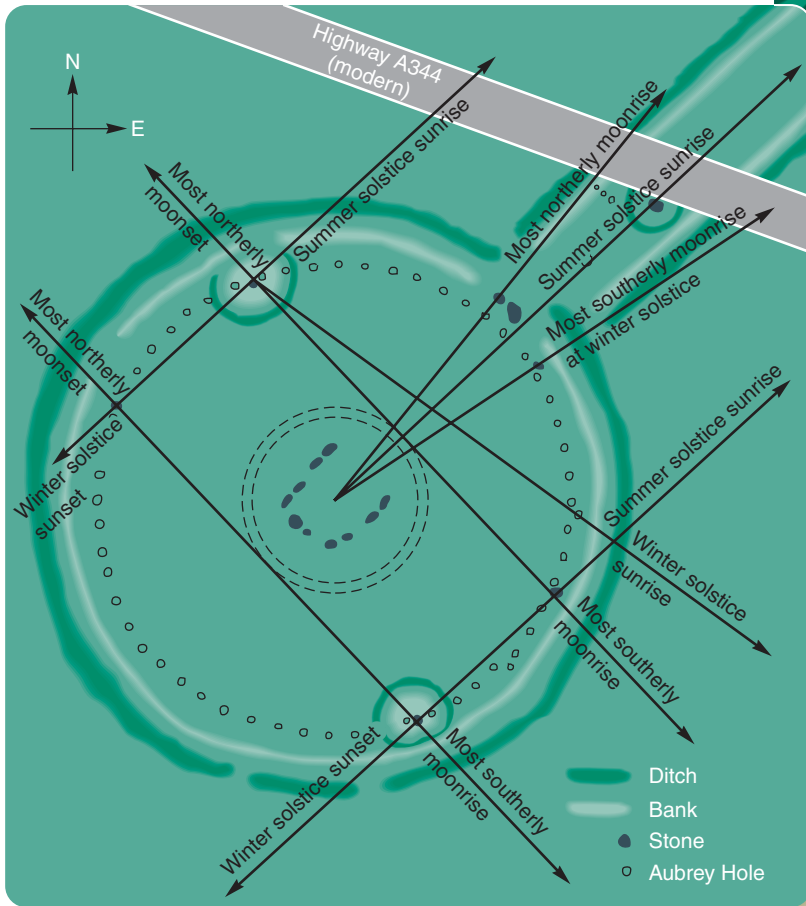
Building astronomical alignments into structures gives them meaning by connecting them with the heavens. Navajo Indians of the American southwest, for example, have for centuries built their hogans with the door facing east so they can greet the rising sun each morning with prayers and offerings.

Some alignments may have served calendrical purposes. The 2000-year-old Temple of Isis in Dendera, Egypt, was built to align with the rising point of the bright star Sirius. The first appearance of this star in the dawn twilight marked the flooding of the Nile, so it was an important calendrical indicator. The link between Sirius and the Nile was described in Egyptian mythology; the goddess Isis was associated with the star Sirius, and her husband, Osiris, was linked to the constellation you know as Orion and also to the Nile, the source of Egypt's agricultural fertility.

An intriguing American site in New Mexico known as the Sun Dagger unfortunately has no surviving mythology to tell its



Sunrise on the morning of the summer solstice



■ **Figure 4-1**

The central horseshoe of upright stones is only the most obvious part of Stonehenge. The best-known astronomical alignment at Stonehenge is the summer solstice sun rising over the Heelstone. Although a number of astronomical alignments have been found at Stonehenge, experts debate their significance. (Photo: Jamie Backman)

■ **Figure 4-2**

Newgrange was built on a small hill in Ireland about 3200 BC. A long passageway extends from the entryway back to the center of the mound, and sunlight shines down the passageway into the central chamber at dawn on the day of the winter solstice. Other passage graves have similar alignments, but their purpose is unknown. (Newgrange: Benelux Press/Index Stock Imagery)





■ **Figure 4-3**

In the ancient Native American settlement known as Chaco Canyon, New Mexico, sunlight shines between two slabs of stone high on the side of 440-foot-high Fajada Butte to form a dagger of light on the cliff face. About noon on the day of the summer solstice, the dagger of light slices through the center of a spiral pecked into the sandstone. (NPS Chaco Culture National Historic Park)

story. At noon on the day of the summer solstice, a narrow dagger of sunlight shines across the center of a spiral carved on a cliff face high above the desert floor (■ Figure 4-3). The purpose of the Sun Dagger is open to debate, but similar examples have been found throughout the American Southwest. It may have been more a symbolic and ceremonial marker than a precise calendrical indicator. In any case, it is just one of the many astronomical alignments that ancient people built into their structures to link themselves with the sky.

Some scholars are examining not ancient structures but small artifacts made thousands of years ago. Scratches on certain bone and stone implements follow a pattern that may record the phases of the moon (■ Figure 4-4). Some scientists contend that humanity's first attempts at writing were stimulated by a desire to record and predict lunar phases.

Archaeoastronomy is uncovering the earliest roots of astronomy and simultaneously revealing some of the first human efforts at systematic inquiry. The most important lesson of archaeoastronomy is that humans don't have to be technologically sophisticated to admire and study the universe. Efforts to understand the sky have been part of human cultures for a long time.

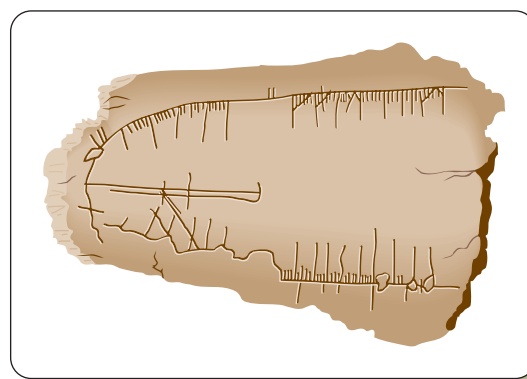
Although the methods of archaeoastronomy can show how ancient people observed the sky, their thoughts about their

universe are in many cases lost. Many cultures had no written language. In other cases, the written record has been lost. Dozens, perhaps hundreds, of beautiful Mayan manuscripts, for instance, were burned by Spanish missionaries who believed that the books were the work of Satan. Only four of these books have survived, and all four contain astronomical references. One contains sophisticated tables that allowed the Maya to predict the motion of Venus and eclipses of the moon. No one will ever know what was burnt.

The fate of the Mayan books illustrates one reason why histories of astronomy usually begin with the Greeks. Some of their writing has survived, and from it you can discover what they thought about the shape and motion of the heavens.

The Astronomy of Greece

Greek astronomy was derived from Babylon and Egypt, but the Greek philosophers took a new approach. Rather than relying on religion and astrology, the Greeks proposed a rational universe whose secrets could be understood through logic and reason. Before you begin your study of the history of



■ **Figure 4-4**

A fragment of a 27,000-year-old mammoth tusk found at Gontzi in Ukraine contains scribe marks on its edge, simplified in this drawing. These markings have been interpreted as a record of four cycles of lunar phases. Although controversial, such finds suggest that some of the first human attempts at recording events in written form were stimulated by astronomical phenomena.

astronomical thought from the classical Greek era through the Renaissance, you should remember the point made in Chapter 1 that the terms *solar system*, *galaxy*, and *universe* have very different meanings. You know now that our solar system, consisting of Earth, the moon, the sun, Earth's sibling planets, their moons, and so on, is your very local neighborhood, much smaller than the Milky Way Galaxy, which in turn is tiny compared with the observable universe. However, from ancient times up through Copernicus's day, it was thought that the whole universe, everything that exists, did not extend much beyond the farthest planet of our solar system. Asking back then whether Earth or the sun is the center of the solar system was the same question as asking whether Earth or the sun is the center of the universe. As you read this chapter, but only this chapter, you can pretend to have the old-fashioned view in which "solar system" and "universe" meant much the same thing.

This new Greek attitude toward studying the heavens with logic and reason was a first step toward modern science, and it was made possible by two early Greek philosophers. Thales of Miletus (c. 624–547 BC) lived and worked in what is now Turkey. He taught that the universe is rational and that the human mind can understand why the universe works the way it does. This view contrasts sharply with that of earlier cultures, which believed that the ultimate causes of things are mysteries beyond human understanding. To Thales and his followers, the mysteries of the universe were mysteries only because they were unknown, not because they were unknowable.

The other philosopher who made the new scientific attitude possible was Pythagoras (c. 570–500 BC). He and his students noticed that many things in nature seem to be governed by geometrical or mathematical relations. Musical pitch, for example, is related in a regular way to the lengths of plucked strings. This led Pythagoras to propose that all nature was underlain by musical principles, by which he meant mathematics. One result of this philosophy was the later belief that the harmony of the celestial movements produced actual music, the music of the spheres. But, at a deeper level, the teachings of Pythagoras made Greek astronomers look at the universe in a new way. Thales said that the universe could be understood, and Pythagoras said that the underlying rules were mathematical.

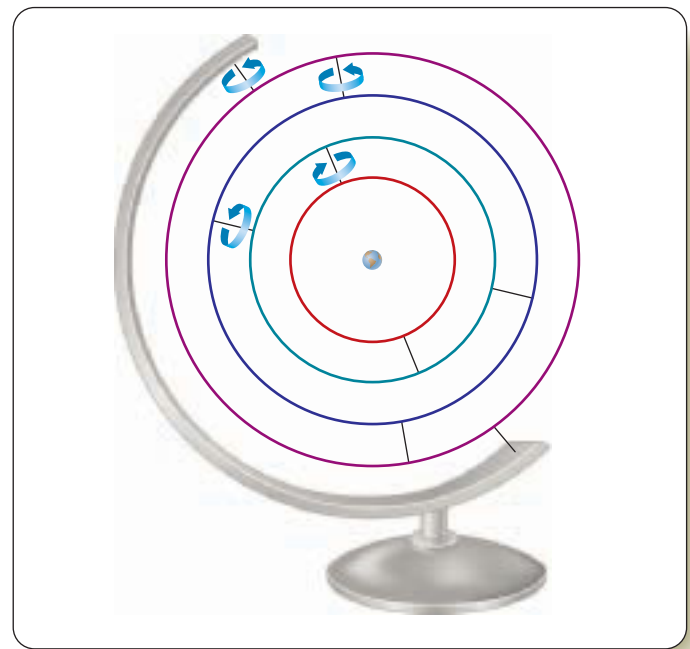
In trying to understand the universe, Greek astronomers did something that Babylonian astronomers had never done—they tried to describe the universe using geometrical forms. Anaximander (c. 611–546 BC) described a universe made up of wheels filled with fire: The sun and moon were holes in the wheels through which the flames could be seen. Philolaus (fifth century BC) argued that Earth moved in a circular path around a central fire (not the sun), which was always hidden behind a counter-Earth located between the fire and Earth. This, by the way, was the first theory to suppose that Earth is in motion.

The great philosopher Plato (428–347 BC) was not an astronomer, but his teachings influenced astronomy for 2000 years. Plato argued that the reality humans see is only a distorted shadow of a perfect, ideal form. If human observations are distorted, then observation can be misleading, and the best path to truth, said Plato, is through pure thought on the ideal forms that underlie nature.

Plato argued that the most perfect geometrical form was the sphere, and therefore, he said, the perfect heavens must be made up of spheres rotating at constant rates and carrying objects around in circles. Consequently, later astronomers tried to describe the motions of the heavens by imagining multiple rotating spheres. This became known as the principle of **uniform circular motion**.

Eudoxus of Cnidus (409–356 BC), a student of Plato, applied this principle when he devised a system of 27 nested spheres that rotated at different rates about different axes to produce a mathematical description of the motions of the universe (■ Figure 4-5).

At the time of the Greek philosophers, it was common to refer to systems such as that of Eudoxus as descriptions of the world, where the word *world* included not only Earth but all of the heavenly spheres. The reality of these spheres was open to debate. Some thought of the spheres as nothing more than mathematical ideas that described motion in the world model, while others began to think of the spheres as real objects made of perfect celestial material. Aristotle, for example, seems to have thought of the spheres as real.



■ **Figure 4-5**

The spheres of Eudoxus explain the motions in the heavens by means of nested spheres rotating about various axes at different rates. Earth is located at the center. In this illustration, only four of the 27 spheres are shown.

Aristotle and the Nature of Earth

Aristotle (384–322 BC), another of Plato’s students, made his own unique contributions to philosophy, history, politics, ethics, poetry, drama, and other subjects (■ Figure 4-6). Because of his sensitivity and insight, he became the greatest authority of antiquity, and his astronomical model was accepted with minor variations for almost 2000 years.

Much of what Aristotle wrote about scientific subjects was wrong, but that is not surprising. The scientific method, with its insistence on evidence and hypothesis, had not yet been invented. Aristotle, like other philosophers of his time, attempted to understand his world by reasoning logically and carefully from first principles. A first principle is something that is held to be obviously true. The perfection of the heavens, meaning that the heavens had to be composed of rotating perfect spheres, was, for Aristotle, a first principle. Once a principle is recognized as true, whatever can be logically derived from it must also be true.

Aristotle believed that the universe was divided into two parts: Earth, imperfect and changeable; and the heavens, perfect and unchanging. Like most of his predecessors, he believed that Earth was the center of the universe, so his model is called a **geocentric universe**. The heavens surrounded Earth, and he added to the model proposed by Eudoxus to bring the total to 55 crystalline spheres turning at different rates and at different angles to carry the sun, moon, and planets across the sky. The lowest sphere, that of the moon, marked the boundary between the changeable imperfect region of Earth and the unchanging perfection of the celestial realm above the moon.

Because he believed Earth to be immobile, Aristotle had to make this entire nest of spheres whirl westward around Earth every 24 hours to produce day and night. The spheres also had to move more slowly with respect to one another to produce the motions of the sun, moon, and planets against the background of the stars. Because his model was geocentric, he taught that Earth



■ **Figure 4-6**

Aristotle, honored on this Greek stamp, wrote on such a wide variety of subjects and with such deep insight that he became the great authority on all matters of learning. His opinions on the nature of Earth and the sky were widely accepted for almost two millennia.

could be the only center of motion, meaning that all of the whirling spheres had to be centered on Earth.

About a century after Aristotle, the Alexandrian philosopher Aristarchus proposed that Earth rotated on its axis and revolved around the sun. This theory is, of course, generally correct, but most of the writings of Aristarchus were lost, and his theory was not well known. Later astronomers rejected any suggestion that Earth could move, because it conflicted with the teachings of the great philosopher Aristotle.

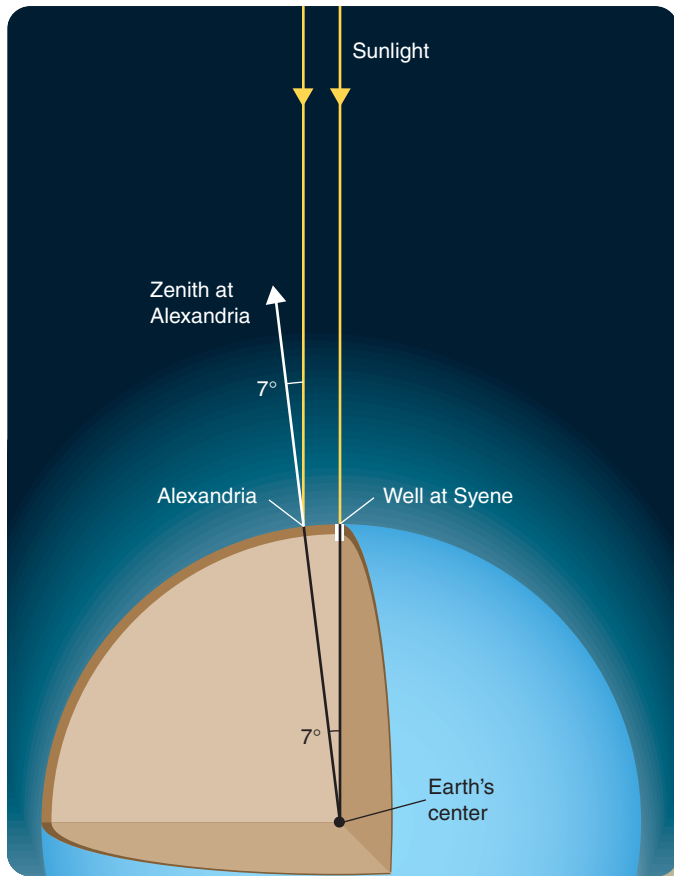
Aristotle had taught that Earth had to be a sphere because it always casts a round shadow during lunar eclipses, but he could only estimate its size. About 200 BC, Eratosthenes, working in the great library in the Egyptian city of Alexandria, found a way to measure Earth’s radius. He learned from travelers that the city of Syene (Aswan) in southern Egypt contained a well into which sunlight shone vertically on the day of the summer solstice. This told him that the sun was at the zenith at Syene; but, on that same day in Alexandria, he noted that the sun was 1/50 of the circumference of the sky (about 7°) south of the zenith.

Because sunlight comes from such a great distance, its rays arrive at Earth traveling almost parallel. That allowed Eratosthenes to use simple geometry to conclude that the distance from Alexandria to Syene was 1/50 of Earth’s circumference (■ Figure 4-7).

To find Earth’s circumference, Eratosthenes had to learn the distance from Alexandria to Syene. Travelers told him it took 50 days to cover the distance, and he knew that a camel can travel about 100 stadia per day. That meant the total distance was about 5000 stadia. If 5000 stadia is 1/50 of Earth’s circumference, then Earth must be 250,000 stadia in circumference, and, dividing by 2π , Eratosthenes found Earth’s radius to be 40,000 stadia.

How accurate was Eratosthenes? The stadium (singular of *stadia*) had different lengths in ancient times. If you assume 6 stadia to the kilometer, then Eratosthenes’s result was too big by only 4 percent. If he used the Olympic stadium, his result was 14 percent too big. In any case, this was a much better measurement of Earth’s radius than Aristotle’s estimate, which was much too small, about 40 percent of the true radius.

You might think this is just a disagreement between two ancient philosophers, but it is related to a **Common Misconception**. Christopher Columbus did not have to convince Queen Isabella that the world was round. At the time of Columbus, all educated people knew that the world was round and not flat, but they weren’t sure how big it was. Columbus, like many others, adopted Aristotle’s diameter for Earth, so he thought Earth was small enough that he could sail west and reach Japan and the Spice Islands of the East Indies. If he had accepted Eratosthenes’ diameter, Columbus would never have risked the voyage. He and his crew were lucky that America was in the way; if there had been open ocean all the way to Japan, they would have starved to death long before they reached land.



■ **Figure 4-7**

On the day of the summer solstice, sunlight fell to the bottom of a well at Syene, but the sun was about $\frac{1}{50}$ of a circle (7°) south of the zenith at Alexandria. From this, Eratosthenes was able to calculate Earth's radius.

Aristotle, Aristarchus, and Eratosthenes were philosophers, but the next person you will meet was a real astronomer who observed the sky in detail. Little is known about Hipparchus, who lived during the second century BC, about two centuries after Aristotle. He is usually credited with the invention of trigonometry, the creation of the first star catalog, and the discovery of precession (Chapter 2). Hipparchus also described the motion of the sun, moon, and planets as following circular paths with Earth near, but not at, their centers. These off-center circles are now known as **eccentrics**. Hipparchus recognized that he could reproduce this motion in a model where the celestial bodies traveled around a small circle that followed a larger circle around Earth. The compounded circular motion that he devised became the key element in the masterpiece of the last great astronomer of classical times, Claudius Ptolemy.

The Ptolemaic Universe

Claudius Ptolemaeus was one of the great astronomer-mathematicians of antiquity. His nationality and birth date are unknown, but around AD 140 he lived and worked in the Greek settlement

at Alexandria in what is now Egypt. He ensured the continued acceptance of Aristotle's universe by transforming it into a sophisticated mathematical model.

When you read **The Ancient Universe** on pages 56–57, notice three important ideas and five new terms that show how first principles influenced early descriptions of the universe and its motions:

- 1 Ancient philosophers and astronomers accepted as first principles that the heavens were geocentric with Earth located at the center and sun, moon, and planets moving in uniform circular motion. It seemed clear to them that Earth was not moving because they saw no *parallax* in the positions of the stars.
- 2 The observed motion of the planets, the evidence, did not fit the theory very well. The *retrograde motion* of the planets was very difficult to explain using geocentrism and uniform circular motion.
- 3 Ptolemy attempted to explain the motion of the planets by devising a small circle, an *epicycle*, that rotated along the edge of a larger circle, and the *deferent*, which enclosed a slightly off-center Earth. An *equant* was a point from which the center of an epicycle appeared to move at a constant rate. That meant the speed of the planets would vary slightly as viewed from Earth.

Ptolemy lived roughly five centuries after Aristotle, and although Ptolemy based his work on the Aristotelian universe, he was interested in a different problem—the motion of the planets. He was a brilliant mathematician, and he was mainly interested in creating a mathematical description of the motions he saw in the heavens. For him, first principles took second place to mathematical precision.

Aristotle's universe, as embodied in the mathematics of Ptolemy, dominated ancient astronomy, but it was wrong. The planets don't follow circles at uniform speeds. At first, the Ptolemaic system predicted the positions of the planets well; but, as centuries passed, errors accumulated. If your watch gains only one second a year, it will keep time well for many years, but the error will gradually become noticeable. So, too, did the errors in the Ptolemaic system gradually accumulate as the centuries passed, but, because of the deep respect people had for the writings of Aristotle, the Ptolemaic system was not abandoned. Islamic and later European astronomers tried to update the system, computing new constants and adjusting epicycles. In the middle of the 13th century, a team of astronomers supported by King Alfonso X of Castile studied the *Almagest* for 10 years. Although they did not revise the theory very much, they simplified the calculation of the positions of the planets using the Ptolemaic system and published the result as *The Alfonsine Tables*, the last great attempt to make the Ptolemaic system of practical use.

The Ancient Universe

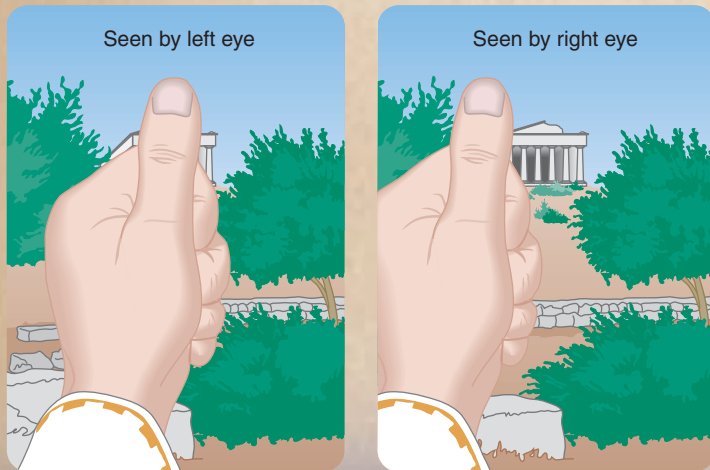
1 For 2000 years, the minds of astronomers were shackled by a pair of ideas. The Greek philosopher Plato argued that the heavens were perfect. Because the only perfect geometrical shape is a sphere, which carries a point on its surface around in a circle, and because the only perfect motion is uniform motion, Plato concluded that all motion in the heavens must be made up of combinations of circles turning at uniform rates. This idea was called uniform circular motion.

Plato's student Aristotle argued that Earth was imperfect and lay at the center of the universe. Such a model is known as a geocentric universe. His model contained 55 spheres turning at different rates and at different angles to carry the seven known planets (the moon, Mercury, Venus, the sun, Mars, Jupiter, and Saturn) across the sky.

Aristotle was known as the greatest philosopher in the ancient world, and for 2000 years his authority chained the minds of astronomers with uniform circular motion and geocentrism. See the model at right.



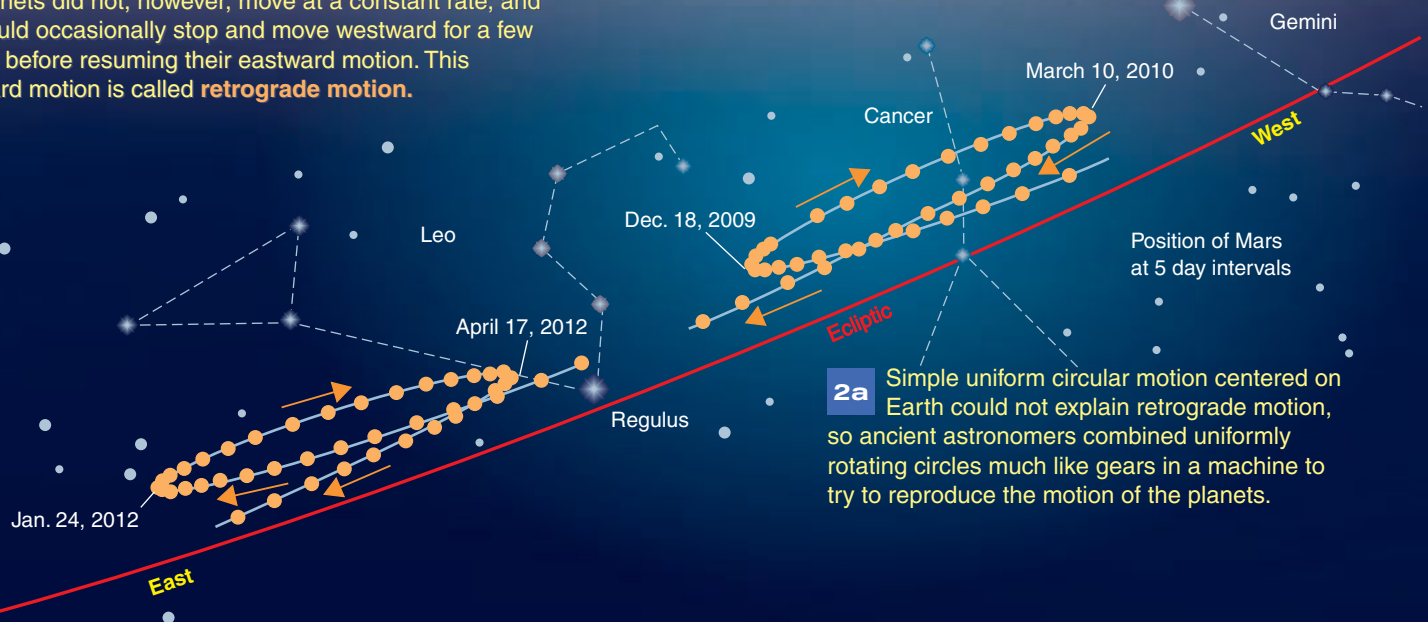
From *Cosmographica* by Peter Apian (1539).



1a Ancient astronomers believed that Earth did not move because they saw no **parallax**, the apparent motion of an object because of the motion of the observer. To demonstrate parallax, close one eye and cover a distant object with your thumb held at arm's length. Switch eyes, and your thumb appears to shift position as shown at left. If Earth moves, ancient astronomers reasoned, you should see the sky from different locations at different times of the year, and you should see parallax distorting the shapes of the constellations. They saw no parallax, so they concluded Earth could not move. Actually, the parallax of the stars is too small to see with the unaided eye.

2 Planetary motion was a big problem for ancient astronomers. In fact, the word *planet* comes from the Greek word for "wanderer," referring to the eastward motion of the planets against the background of the fixed stars. The planets did not, however, move at a constant rate, and they could occasionally stop and move westward for a few months before resuming their eastward motion. This backward motion is called **retrograde motion**.

Every 2.14 years, Mars passes through a retrograde loop. Two successive loops are shown here. Each loop occurs farther east along the ecliptic and has its own shape.



2a Simple uniform circular motion centered on Earth could not explain retrograde motion, so ancient astronomers combined uniformly rotating circles much like gears in a machine to try to reproduce the motion of the planets.

3 Uniformly rotating circles were key elements of ancient astronomy. Claudius Ptolemy created a mathematical model of the Aristotelian universe in which the planet followed a small circle called the **epicycle** that slid around a larger circle called the **deferent**. By adjusting the size and rate of rotation of the circles, he could approximate the retrograde motion of a planet. See illustration at right.

To adjust the speed of the planet, Ptolemy supposed that Earth was slightly off center and that the center of the epicycle moved such that it appeared to move at a constant rate as seen from the point called the **equant**.

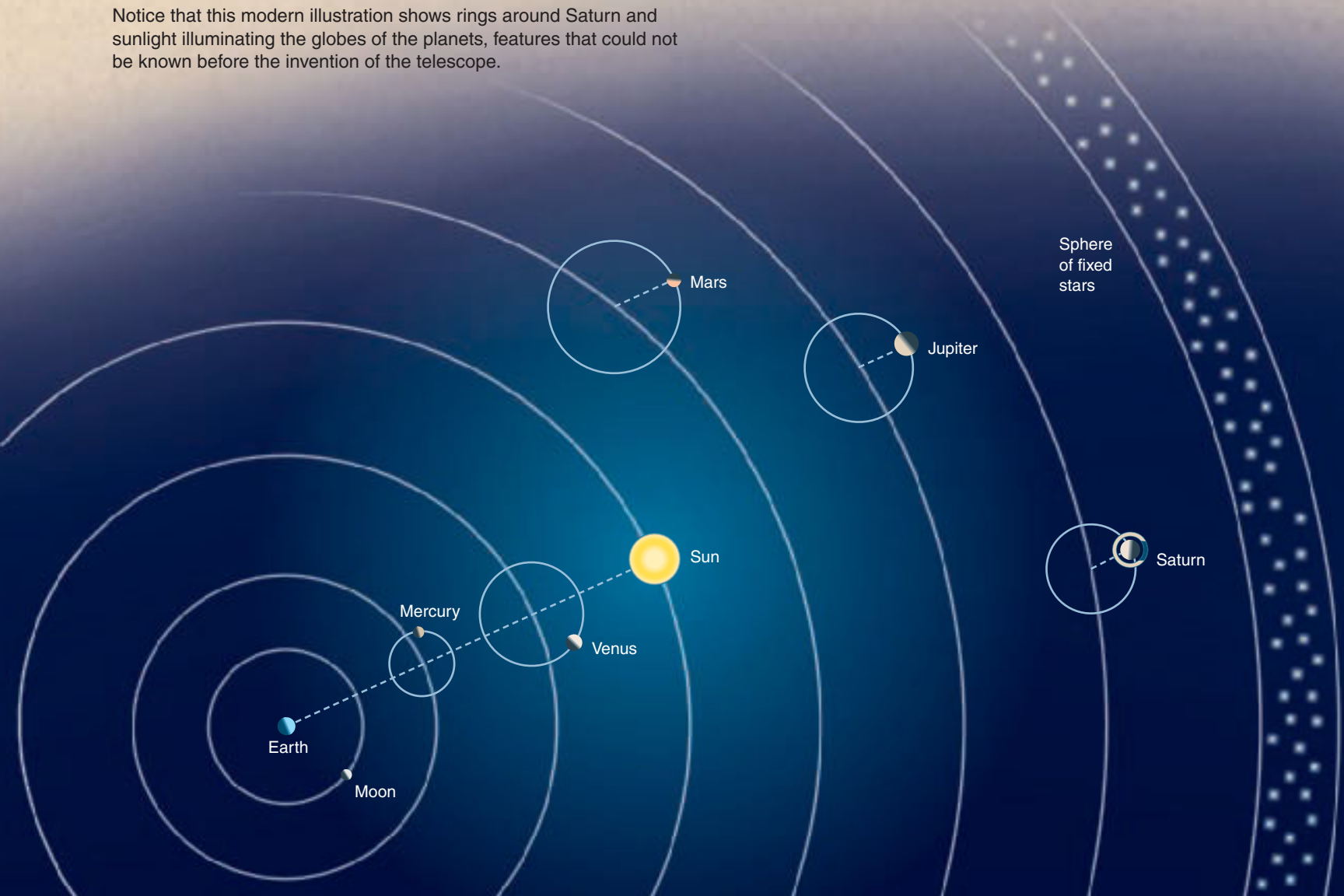
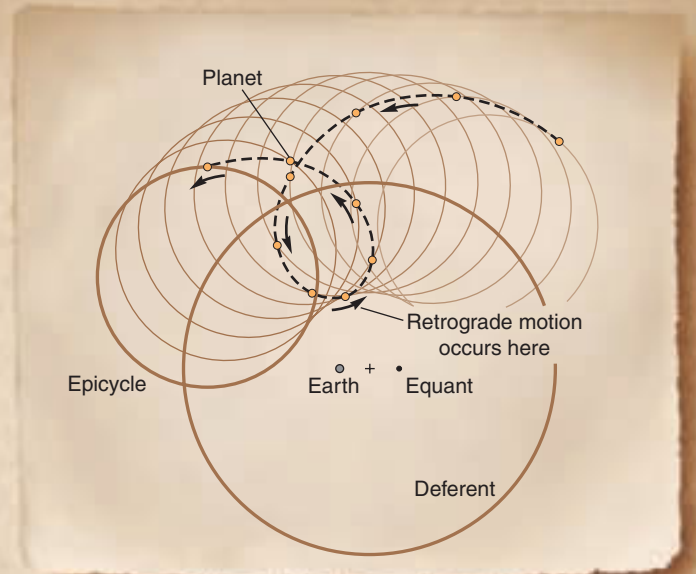
To further adjust his model, Ptolemy added small epicycles (not shown here) riding on top of larger epicycles, producing a highly complex model.

3a Ptolemy's great book *Mathematical Syntaxis* (c. AD 140) contained the details of his model. Islamic astronomers preserved and studied the book through the Middle Ages, and they called it *Al Magisti* (The Greatest). When the book was found and translated from Arabic to Latin in the 12th century, it became known as *Almagest*.

3b The Ptolemaic model of the universe shown below was geocentric and based on uniform circular motion. Note that Mercury and Venus were treated differently from the rest of the planets. The centers of the epicycles of Mercury and Venus had to remain on the Earth–Sun line as the sun circled Earth through the year.

Equants and smaller epicycles are not shown here. Some versions contained nearly 100 epicycles as generations of astronomers tried to fine-tune the model to better reproduce the motion of the planets.

Notice that this modern illustration shows rings around Saturn and sunlight illuminating the globes of the planets, features that could not be known before the invention of the telescope.



SCIENTIFIC ARGUMENT

How did the astronomy of Hipparchus and Ptolemy violate the principles of the early Greek philosophers Plato and Aristotle?

Today, scientific arguments depend on evidence and theory; but, in classical times, they started from first principles. Hipparchus and Ptolemy lived very late in the history of classical astronomy, and they concentrated more on the mathematical problems and less on philosophical principles. They replaced the perfect spheres of Plato with nested circles in the form of epicycles and deferents. Earth was moved slightly away from the center of the deferent, so their models of the universe were not exactly geocentric, and the epicycles moved uniformly only as seen from the equant. The celestial motions were no longer precisely uniform, and the principles of geocentrism and uniform circular motion were weakened.

The work of Hipparchus and Ptolemy led eventually to a new understanding of the heavens, but first astronomers had to abandon uniform circular motion. Construct an argument in the classical style based on first principles to answer the following: **Why did Plato argue for uniform circular motion?**

4-2 The Copernican Revolution

YOU WOULD NOT HAVE EXPECTED NICOLAUS COPERNICUS to trigger a revolution in astronomy and science. He was born in 1473 to a merchant family in Poland. Orphaned at the age of 10, he was raised by his uncle, an important bishop, who sent him to the University of Cracow and then to the best universities in Italy. There he studied law and medicine before pursuing a life-long career as an important administrator in the Church. Nevertheless, he had a passion for astronomy (■ Figure 4-8).



■ **Figure 4-8**

Nicolaus Copernicus (1473–1543) pursued a lifetime career in the Church, but he was also a talented mathematician and astronomer. His work triggered a revolution in human thought. These stamps were issued in 1973 to mark the 500th anniversary of his birth.

The Copernican Model

If you had sat beside Copernicus in his astronomy classes, you would have studied the Ptolemaic universe. The central location of Earth was widely accepted, and everyone knew that the heavens moved in uniform circular motion. For most scholars, questioning these principles was not an option because, over the course of centuries, Aristotle's proposed geometry had become

linked with Christian teachings. According to the Aristotelian universe, the most perfect region was in the heavens and the most imperfect at Earth's center. This classical geocentric universe matched the commonly held Christian geometry of heaven and hell, so anyone who criticized the Ptolemaic model was not only questioning Aristotle's geometry but also indirectly challenging belief in heaven and hell.

For this reason, Copernicus probably found it difficult at first to consider alternatives to the Ptolemaic universe. Throughout his life, he was associated with the Catholic Church, which had adopted many of Aristotle's ideas. His uncle was an important bishop in Poland, and, through his uncle's influence, Copernicus was appointed a canon at the cathedral in Frauenberg at the unusually young age of 24. (A canon was not a priest but a Church administrator.) This gave Copernicus an income, although he continued his studies at the universities in Italy. When he left the universities, he joined his uncle and served as his secretary and personal physician until his uncle died in 1512. At that point, Copernicus moved into quarters adjoining the cathedral in Frauenburg, where he served as canon for the rest of his life.

His close connection with the Church notwithstanding, Copernicus began to consider an alternative to the Ptolemaic universe, probably while he was still at university. Sometime before 1514, he wrote an essay proposing a model of a **heliocentric universe** in which the sun, not Earth, was the center of that universe. To explain the daily and annual cycles of the sky, he proposed that Earth rotates on its axis and revolves around the sun. He distributed this commentary in handwritten form, without a title, and in some cases anonymously, to friends and astronomical correspondents. He may have been cautious out of modesty, or out of respect for the Church, or out of fear that his revolutionary ideas would be attacked unfairly. After all, the place of Earth was a controversial theological subject. Although this early essay discusses every major aspect of his later work, it did not include observations and calculations. His ideas needed supporting evidence, so he began gathering observations and making detailed calculations to be published as a book that would demonstrate the truth of his revolutionary idea.

De Revolutionibus

Copernicus worked on his book *De Revolutionibus Orbium Coelestium* (*The Revolutions of the Celestial Spheres*) over a period of many years and was essentially finished by about 1529; yet he hesitated to publish it even though other astronomers already knew of his theories. Even Church officials, concerned about the reform of the calendar, sought his advice and looked forward to the publication of his book.

One reason he hesitated was that he knew that the idea of a heliocentric universe would be highly controversial. This was a time of rebellion in the Church—Martin Luther (1483–1546)

was speaking harshly about fundamental Church teachings, and others, both scholars and scoundrels, were questioning the Church's authority. Even matters as abstract as astronomy could stir controversy. Remember, too, that Earth's place in astronomical theory was linked to the geometry of heaven and hell, so moving Earth from its central place was a controversial and perhaps heretical idea.

Another reason Copernicus may have hesitated to publish was that his work was incomplete. His model could not accurately predict planetary positions, so he continued to refine it. Finally in 1540 he allowed the visiting astronomer Joachim Rheticus (1514–1576) to publish an account of the Copernican universe in Rheticus's book *Prima Narratio (First Narrative)*. In 1542, Copernicus sent the manuscript for *De Revolutionibus* off to be printed. He died in the spring of 1543 before the printing was completed.

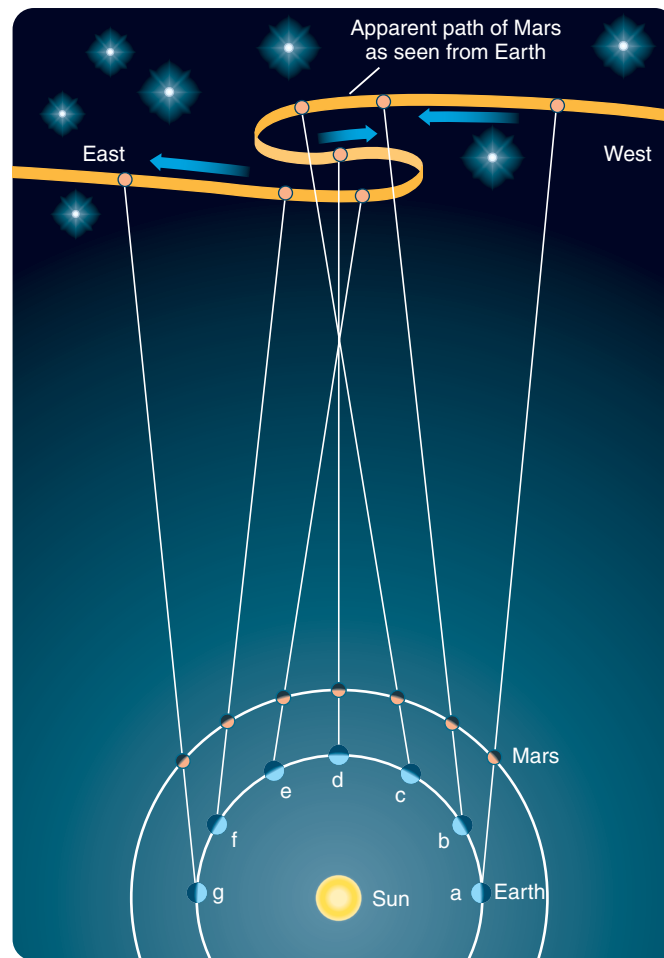
The most important idea in the book was the location of the sun at the center of the universe. That single innovation had an astonishing consequence—the retrograde motion of the planets was immediately explained in a straightforward way without the large epicycles that Ptolemy had used.

In the Copernican system, Earth moves faster along its orbit than the planets that lie farther from the sun. Consequently, Earth periodically overtakes and passes these planets. To visualize this, imagine that you are in a race car, driving rapidly along the inside lane of a circular racetrack. As you pass slower cars driving in the outer lanes, they fall behind, and if you did not realize you were moving, it would look as if the cars in the outer lanes occasionally slowed to a stop and then backed up for a short interval.

■ Figure 4-9 shows how the same thing happens as Earth passes a planet such as Mars. Although Mars moves steadily along its orbit, as seen from Earth it appears to slow its eastward motion. As Earth passes Mars (d), Mars appears to move westward (retrograde) as Earth passes it. This happens to any planet whose orbit lies outside Earth's orbit, so the ancient astronomers saw Mars, Jupiter, and Saturn occasionally move retrograde along the ecliptic. Because the planetary orbits do not lie in precisely the same plane, a planet does not resume its eastward motion in precisely the same path it followed earlier. Consequently, it describes a loop whose shape depends on the angle between the orbital planes.

Copernicus could explain retrograde motion without epicycles, and that was impressive. The Copernican system was elegant and simple compared with the whirling epicycles and off-center equants of the Ptolemaic system. You can see Copernicus's own diagram for his heliocentric system in ■ Figure 4-10a. However, *De Revolutionibus* failed in one critical way—the Copernican model could not predict the positions of the planets any more accurately than the Ptolemaic system could. To understand why it failed, you must understand Copernicus and his world.

Copernicus proposed a revolutionary idea when he made the planetary system heliocentric, but he was a classical astronomer with tremendous respect for the old concept of uniform circular

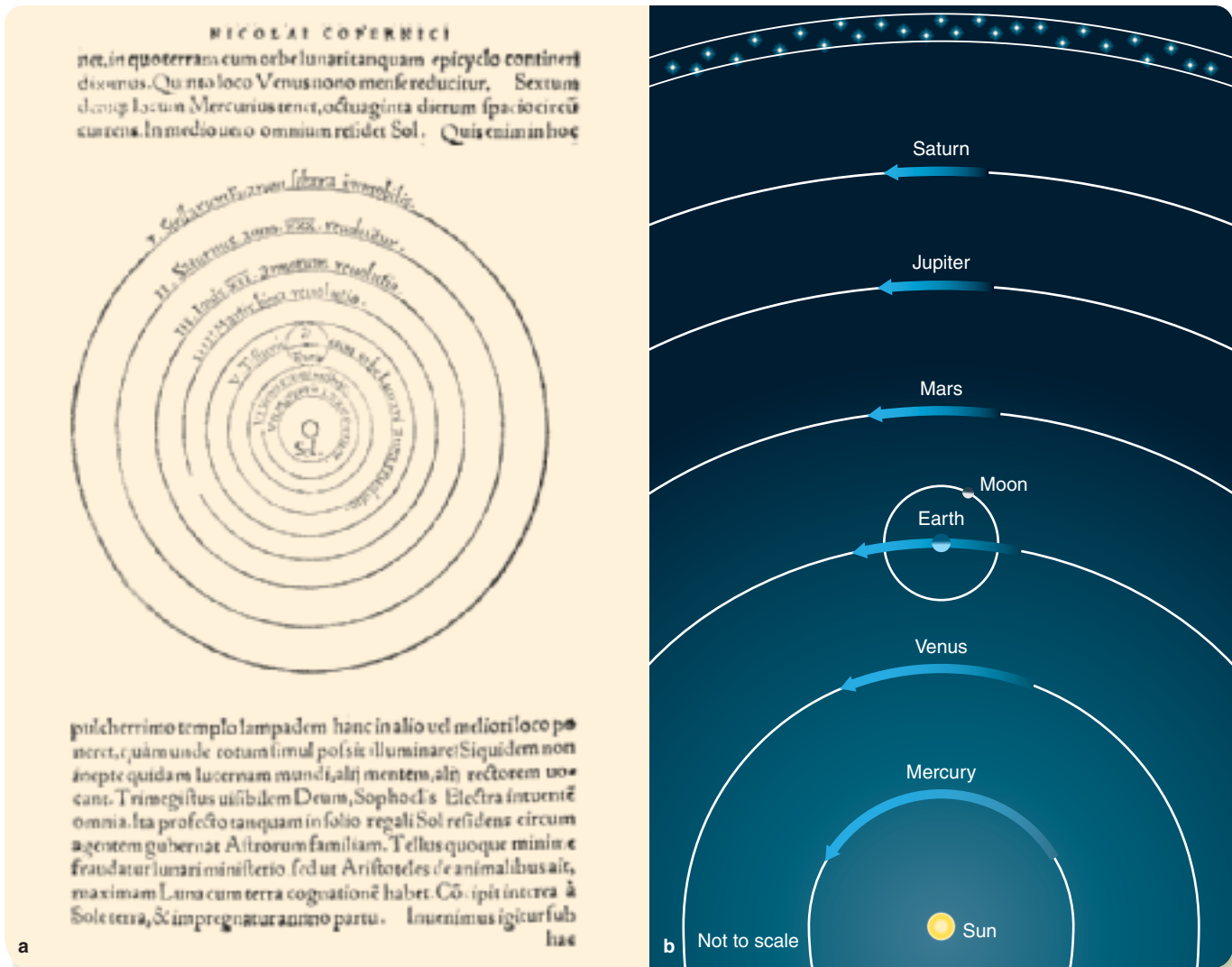


■ **Figure 4-9**

The Copernican explanation of retrograde motion. As Earth overtakes Mars (a–c), Mars appears to slow its eastward motion. As Earth passes Mars (d), Mars appears to move westward. As Earth draws ahead of Mars (e–g), Mars resumes its eastward motion against the background stars. The positions of Earth and Mars are shown at equal intervals of one month.

motion. In fact, Copernicus objected strongly to Ptolemy's use of the equant. It seemed arbitrary to Copernicus, an obvious violation of the elegance of Aristotle's philosophy of the heavens. Copernicus called equants "monstrous" because they undermined both geocentrism and uniform circular motion. In devising his model, Copernicus demonstrated a strong belief in uniform circular motion.

Although he did not need epicycles to explain retrograde motion, Copernicus quickly discovered that the sun, moon, and planets suffered other small variations in their motions that he could not explain using uniform circular motion centered on the sun. Today astronomers recognize those variations as the result of planets following elliptical orbits, but because Copernicus held firmly to uniform circular motion, he had to introduce small epicycles to try to reproduce these minor variations in the motions of the sun, moon, and planets.



■ **Figure 4-10**

(a) The Copernican universe as reproduced in *De Revolutionibus*. Earth and all the known planets revolve in separate circular orbits about the sun (Sol) at the center. The outermost sphere carries the immobile stars of the celestial sphere. Notice the orbit of the moon around Earth (Terra). (Yerkes Observatory) (b) The model was elegant not only in its arrangement of the planets but also in their motions. Orbital speed (blue arrows) decreased from Mercury, the fastest, to Saturn, the slowest. Compare the elegance of this model with the complexity of the Ptolemaic model on page 57.

Because Copernicus imposed uniform circular motion on his model, it could not accurately predict the motions of the planets. *The Prutenic Tables* (1551) were based on the Copernican model, and they were not significantly more accurate than the 13th-century *Alfonsine Tables* that were based on Ptolemy's model. Both could be in error by as much as 2° , which is four times the angular diameter of the full moon.

The Copernican *model* is inaccurate. It includes uniform circular motion and consequently does not precisely describe the motions of the planets. But the Copernican *hypothesis* that the universe is heliocentric is correct, considering how little

astronomers of the time knew of other stars and galaxies. The planets circle the sun, not Earth, so the universe that Copernicus knew was heliocentric.

Although astronomers throughout Europe read and admired *De Revolutionibus*, they did not immediately accept the Copernican hypothesis. The mathematics was elegant, and the astronomical observations and calculations were of tremendous value; but few astronomers believed, at first, that the sun actually was the center of the planetary system and that Earth moved. How the Copernican hypothesis was gradually recognized as correct has been called the Copernican Revolution because it was

Scientific Revolutions

How do scientific revolutions occur? You might think from what you know of the scientific method that science grinds forward steadily as new theories are tested against evidence and accepted or rejected. In fact, science sometimes leaps forward in scientific revolutions. The Copernican Revolution is often cited as the perfect example; in a few decades, astronomers rejected the 2000-year-old geocentric model and adopted the heliocentric model. Why does that happen? It's all because scientists are human.

The American philosopher of science Thomas Kuhn has referred to a commonly accepted set of scientific ideas and assumptions as a scientific **paradigm**. The pre-Copernican astronomers shared a geocentric paradigm that included uniform circular motion, geocentrism, and the perfection of the heavens. Although they were intelligent, they were prisoners of that paradigm. A scientific

paradigm is powerful because it shapes your perceptions. It determines what you judge to be important questions and what you judge to be significant evidence. Consequently, the ancient astronomers could not recognize how their geocentric paradigms limited what they understood.

You will see here how the work of Copernicus, Galileo, and Kepler overthrew the geocentric paradigm. Scientific revolutions occur when the deficiencies of the old paradigm build up until finally a scientist has the insight to think “outside the box.” Pointing out the failings of the old ideas and proposing a new paradigm with supporting evidence is like poking a hole in a dam; suddenly the pressure is released, and the old paradigm is swept away.

Scientific revolutions are exciting because they give you a dramatic new understanding of nature, but they are also times of conflict as new insights sweep away old ideas.



The ancients believed the stars were attached to a stary sphere. (NOAO and Nigel Sharp)

not just the adoption of a new idea but a total change in the way astronomers, and, in fact, all of humanity, thought about the place of the Earth (**How Do We Know? 4-1**).

There are probably a number of reasons why the Copernican hypothesis gradually won support, including the revolutionary temper of the times, but the most important factor may have been the elegance of the idea. Placing the sun at the center of the universe produced a symmetry among the motions of the planets that is pleasing to the eye as well as to the intellect (Figure 4-10b). In the Ptolemaic model, Mercury and Venus were treated differently from the rest of the planets; their epicycles had to remain centered on the Earth–sun line. In the Copernican model, all of the planets were treated the same. They all followed orbits that circled the sun at the center. Furthermore, their speed depended in an orderly way on their distance from the sun, with those closest moving fastest.

The most astonishing consequence of the Copernican hypothesis was not what it said about the sun but what it said about Earth. By placing the sun at the center, Copernicus made Earth into a planet, moving along an orbit like the other planets. By making Earth a planet, Copernicus revolutionized humanity's view of its place in the universe and triggered a controversy that would eventually bring the astronomer Galileo Galilei before the Inquisition. This controversy over the apparent conflict between scientific knowledge and philosophical and theological ideals continues even today.

SCIENTIFIC ARGUMENT

Why would you say the Copernican hypothesis was correct but the model was inaccurate?

To build this argument, you must distinguish carefully between a hypothesis and a model. The Copernican hypothesis was that the sun and not Earth was the center of the universe. Given the limited knowledge of the Renaissance astronomers about distant stars and galaxies, that hypothesis was correct.

The Copernican model, however, included not only the heliocentric hypothesis but also uniform circular motion. The model is inaccurate because the planets don't really follow circular orbits, and the small epicycles that Copernicus added to his model never quite reproduced the motions of the planets.

Now build a new argument. The Copernican hypothesis won converts because it is elegant and can explain retrograde motion. **How does its explanation of retrograde motion work, and how is it more elegant than the Ptolemaic explanation?**

4-3 Planetary Motion

THE COPERNICAN HYPOTHESIS solved the problem of the place of Earth, but it didn't explain planetary motion. If planets don't move in uniform circular motion, how do they move? The puzzle of planetary motion was solved during the century following the death of Copernicus through the work of two men. One compiled the observations, and the other did the analysis.

Tycho Brahe

Tycho Brahe (1546–1601) was not a churchman like Copernicus but rather a nobleman from an important family, educated at the finest universities. He was well known for his vanity and his lordly manners, and by all accounts he was a proud and haughty nobleman. Tycho's disposition was not improved by a dueling injury from his university days. His nose was badly disfigured, and for the rest of his life he wore false noses made of gold and silver, stuck on with wax (■ Figure 4-11).

Although Tycho officially studied law at the university, his real passions were mathematics and astronomy, and early in his university days he began measuring the positions of the planets in the sky. In 1563, Jupiter and Saturn passed very near each other in the sky, nearly merging into a single point on the night of August 24. Tycho found that the *Alfonsine Tables* were a full month in error and that the *Prutenic Tables* were in error by a number of days.

In 1572, a “new star” (now called Tycho's supernova) appeared in the sky, shining more brightly than Venus, and Tycho carefully measured its position. According to classical astronomy, the new star represented a change in the heavens and therefore had to lie below the sphere of the moon. To Tycho, who still believed in a

geocentric universe, that meant that the new star should show parallax, meaning that it would appear slightly too far east as it rose and slightly too far west as it set (■ Figure 4-12). But Tycho saw no parallax in the position of the new star, so he concluded that it must lie above the sphere of the moon and was probably on the starry sphere itself. This contradicted Aristotle's conception of the starry sphere as perfect and unchanging.

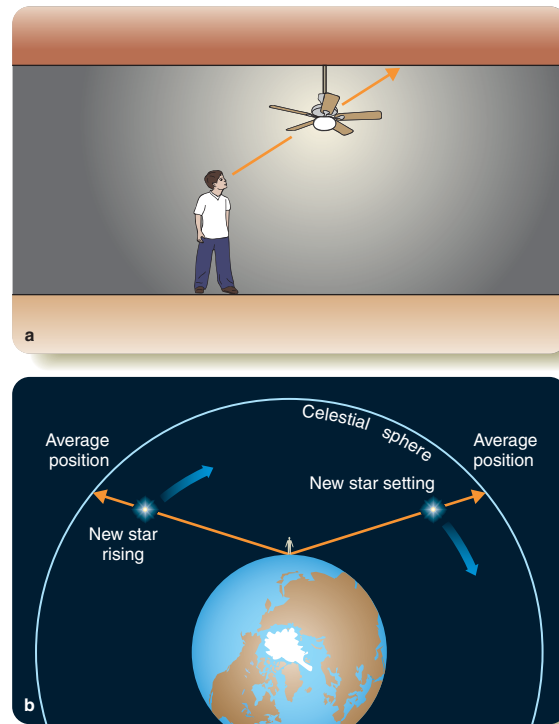
No one before Tycho could have made this discovery because no one had ever measured the positions of celestial objects so accurately. Tycho had great confidence in the precision of his measurements, and he had studied astronomy thoroughly, so when he failed to detect parallax for the new star, he knew it was important evidence against the Ptolemaic theory. He announced his discovery in a small book, *De Stella Nova (The New Star)*, published in 1573.

The book attracted the attention of astronomers throughout Europe, and soon Tycho's family introduced him to the court of the Danish King Frederik II, where he was offered funds to build an observatory on the island of Hveen just off the Danish coast. To support his observatory, Tycho was given a steady income as lord of a coastal district from which he collected rents. (He was not a popular landlord.) On Hveen, Tycho constructed



■ **Figure 4-11**

Tycho Brahe (1546–1601) was, during his lifetime, the most famous astronomer in the world. Proud of his noble rank, he wears the elephant medal awarded him by the king of Denmark. His artificial nose is suggested in this engraving. Tycho Brahe's model of the universe retained the first principles of classical astronomy; it was geocentric with the sun and moon revolving around Earth, but the planets revolved around the sun. All motion was along circular paths.



■ **Figure 4-12**

(a) A fan hanging below a ceiling displays parallax when seen from the side. (b) According to Aristotle, the new star of 1572 should have been located below the sphere of the moon; consequently, reasoned Tycho, it should display parallax and be seen east of its average position as it was rising and west of its average position when it was setting. Because he did not detect this daily parallax, he concluded that the new star of 1572 had to lie on the celestial sphere.

a luxurious home with six towers especially equipped for astronomy and populated it with servants, assistants, and a dwarf to act as jester. Soon Hveen was an international center of astronomical study.

Tycho Brahe's Legacy

Tycho made no direct contribution to astronomical theory. Because he could measure no parallax for the stars, he concluded that Earth had to be stationary, thus rejecting the Copernican hypothesis. However, he also rejected the Ptolemaic model because of its inaccuracy. Instead he devised a complex model in which Earth was the immobile center of the universe around which the sun and moon moved. The other planets circled the sun (Figure 4-11). The model thus incorporated part of the Copernican model, but in it Earth—not the sun—was stationary. In this way, Tycho preserved the central immobile Earth. Although Tycho's model was very popular at first, the Copernican model replaced it within a century. The true value of Tycho's work was observational. Because he was able to devise new and better instruments, he was able to make highly accurate observations of the position of the stars, sun, moon, and planets. Tycho had no telescopes—they were not invented until the next century—so his observations were made by the unaided eye peering along sight-lines. He and his assistants made precise observations for 20 years at Hveen.

Unhappily for Tycho, King Fredrik II died in 1588, and his young son took the throne. Suddenly, Tycho's temper, vanity, and noble presumptions threw him out of favor. In 1596, taking most of his instruments and books of observations, he went to Prague, the capital of Bohemia, and became imperial mathematician to the Holy Roman Emperor Rudolph II. His goal was to revise the *Alfonsine Tables* and publish the result as a monument to his new patron. It would be called the *Rudolphine Tables*.

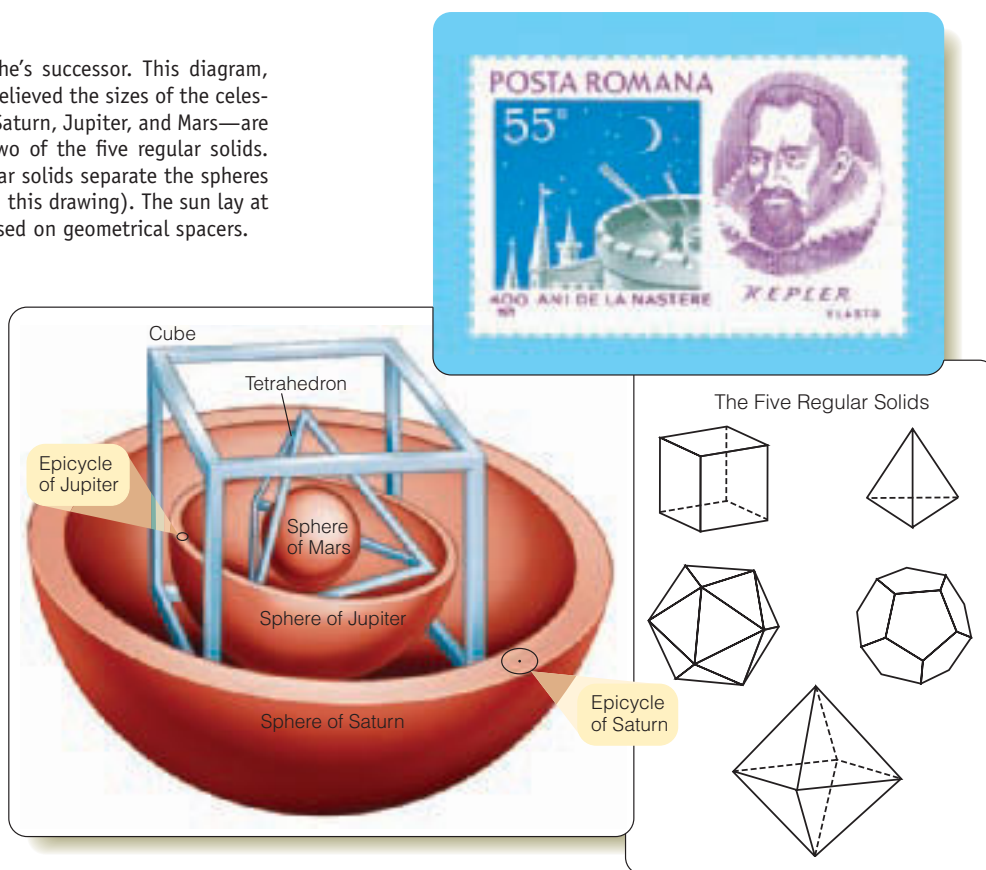
Tycho did not intend to base the *Rudolphine Tables* on the Ptolemaic system but rather on his own Tyconic system, proving once and for all the validity of his hypothesis. To assist him, he hired a few mathematicians and astronomers, including one Johannes Kepler. Then, in November 1601, Tycho collapsed at a nobleman's home. Before he died, 11 days later, he asked Rudolph II to make Kepler imperial mathematician. The newcomer became Tycho's replacement (though at one-sixth Tycho's salary).

Kepler: An Astronomer of Humble Origins

No one could have been more different from Tycho Brahe than Johannes Kepler (■ Figure 4-13). Kepler was born in 1571 to a poor family in a region that is now part of southwest Germany. His father was unreliable and shiftless, principally employed as a mercenary soldier fighting for whoever paid enough. He was often absent for long periods and finally failed to return from a military

■ **Figure 4-13**

Johannes Kepler (1571–1630) was Tycho Brahe's successor. This diagram, based on one drawn by Kepler, shows how he believed the sizes of the celestial spheres carrying the outer three planets—Saturn, Jupiter, and Mars—are determined by spacers (blue) consisting of two of the five regular solids. Inside the sphere of Mars, the remaining regular solids separate the spheres of the Earth, Venus, and Mercury (not shown in this drawing). The sun lay at the very center of this Copernican universe based on geometrical spacers.



expedition. Kepler's mother was apparently an unpleasant and unpopular woman. She was accused of witchcraft in later years, and Kepler had to defend her in a trial that dragged on for three years. She was finally acquitted, but died the following year.

In spite of family disadvantages and chronic poor health, Kepler did well in school, winning promotion to a Latin school and eventually a scholarship to the university at Tübingen, where he studied to become a Lutheran pastor. During his last year of study, Kepler accepted a job in Graz teaching mathematics and astronomy, a job he resented because he knew little about the subjects. Evidently he was not a good teacher—he had few students his first year and none at all his second. His superiors put him to work teaching a few introductory courses and preparing an annual almanac that contained astronomical, astrological, and weather predictions. Through good luck, in 1595 some of his weather predictions were fulfilled, and he gained a reputation as an astrologer and seer. Even in later life he earned money from his almanacs.

While still a college student, Kepler had become a believer in the Copernican hypothesis, and at Graz he used his extensive spare time to study astronomy. By 1596, the same year Tycho arrived in Prague, Kepler was sure he had solved the mystery of the universe. That year he published a book called *The Forerunner of Dissertations on the Universe, Containing the Mystery of the Universe*. The book, like nearly all scientific works of that age, was written in Latin and is now known as *Mysterium Cosmographicum*.

By modern standards, the book contains almost nothing of value. It begins with a long appreciation of Copernicanism and then goes on to speculate on the reasons for the spacing of the planetary orbits. Kepler assumed that the heavens could be described by only the most perfect of shapes. Therefore he felt that he had found the underlying architecture of the universe in the sphere plus the five regular solids.* In Kepler's model, the five regular solids became spacers for the orbits of the six planets which were represented by nested spheres (Figure 4-13). In fact, Kepler concluded that there could be only six planets (Mercury, Venus, Earth, Mars, Jupiter, and Saturn) because there were only five regular solids to act as spacers between their spheres. He provided astrological, numerical, and even musical arguments for his theory.

The second half of the book is no better than the first, but it has one virtue—as Kepler tried to fit the five solids to the planetary orbits, he demonstrated that he was a talented mathematician and that he was well versed in astronomy. He sent copies of his book to Tycho on Hveen and to Galileo in Rome.

Joining Tycho

Life was unsettled for Kepler because of the persecution of Protestants in the region, so when Tycho Brahe invited him to Prague in 1600, Kepler went readily, eager to work with the famous

*The five regular solids, also known as the Platonic solids, are the tetrahedron, cube, octahedron, dodecahedron, and icosahedron. They were considered perfect because the faces and the angles between the faces are the same at every corner.

Danish astronomer. Tycho's sudden death in 1601 left Kepler, the new imperial mathematician, in a position to use the observations from Hveen to analyze the motions of the planets and complete *The Rudolphine Tables*. Tycho's family, recognizing that Kepler was a Copernican and guessing that he would not follow the Tyconic system in completing *The Rudolphine Tables*, sued to recover the instruments and books of observations. The legal wrangle went on for years. Tycho's family did get back the instruments Tycho had brought to Prague, but Kepler had the books, and he kept them.

Whether Kepler had any legal right to Tycho's records is debatable, but he put them to good use. He began by studying the motion of Mars, trying to deduce from the observations how the planet moved. By 1606, he had solved the mystery, this time correctly. The orbit of Mars is an ellipse and not a circle, he realized, and with that he abandoned the 2000-year-old belief in the circular motion of the planets. But even this insight was not enough to explain the observations. The planets do not move at uniform speeds along their elliptical orbits. Kepler's analysis showed that they move faster when close to the sun and slower when farther away. With those two brilliant discoveries, Kepler abandoned uniform circular motion and finally solved the puzzle of planetary motion. He published his results in 1609 in a book called *Astronomia Nova (New Astronomy)*.

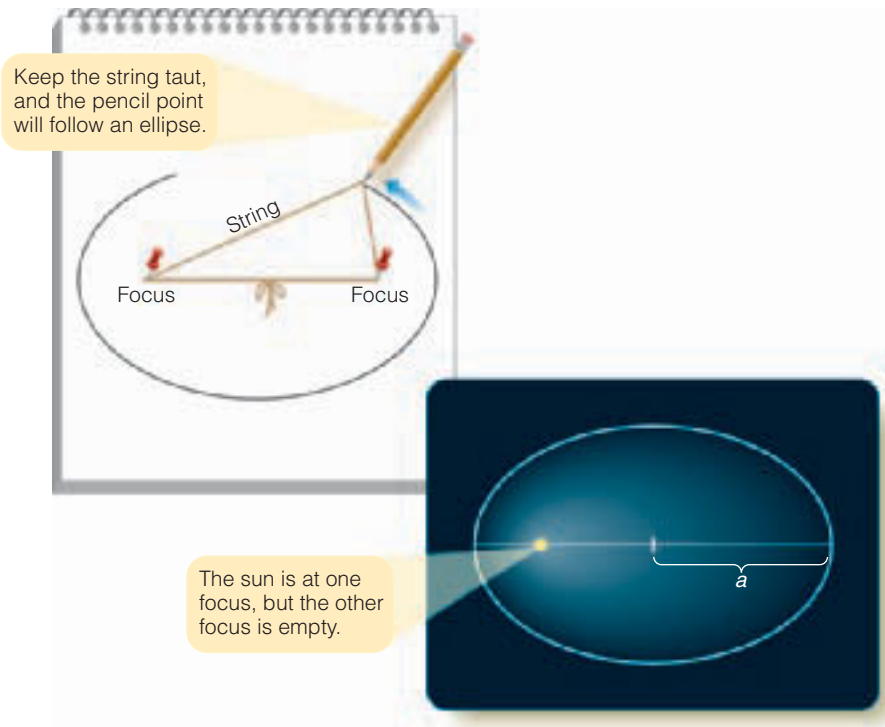
In spite of the abdication of Rudolph II in 1611, Kepler continued his astronomical studies. He wrote about a supernova that appeared in 1604 (now known as Kepler's supernova) and about comets, and he wrote a textbook about Copernican astronomy. In 1619, he published *Harmonice Mundi (The Harmony of the World)*, in which he returned to the cosmic mysteries of *Mysterium Cosmographicum*. The only thing of note in *Harmonice Mundi* is his discovery that the radii of the planetary orbits are related to the planets' orbital periods. That and his two previous discoveries are so important that they have become known as the three most fundamental rules of orbital motion.

Kepler's Three Laws of Planetary Motion

Although Kepler dabbled in the philosophical arguments of his day, he was at heart a mathematician, and his triumph was his explanation of the motion of the planets. The key to his solution was the ellipse.

An **ellipse** is a figure that can be drawn around two points, called the *foci*, in such a way that the distance from one focus to any point on the ellipse and back to the other focus equals a constant. This makes it easy to draw ellipses using two thumbtacks and a loop of string. Press the thumbtacks into a board, loop the string about the tacks, and place a pencil in the loop. If you keep the string taut as you move the pencil, it traces out an ellipse (■ Figure 4-14).

The geometry of an ellipse is described by two simple numbers. The **semimajor axis**, a , is half of the longest diameter, as you can see in Figure 4-14. The **eccentricity**, e , of an ellipse is half the distance between the foci divided by the semimajor axis.



■ **Figure 4-14**

The geometry of elliptical orbits: Drawing an ellipse with two tacks and a loop of string is easy. The semimajor axis, a , is half of the longest diameter. The sun lies at one of the foci of the elliptical orbit of a planet.

The eccentricity of an ellipse tells you its shape; if e is nearly equal to one, the ellipse is very elongated. If e is closer to zero, the ellipse is more circular. To draw a circle with the string and tacks shown Figure 4-14, you would have to move the two thumbtacks together because a circle is really just an ellipse with eccentricity equal to zero. Try fiddling with real thumbtacks and string, and you'll be surprised how easy it is to draw graceful, smooth ellipses with various eccentricities.

Ellipses are a prominent part of Kepler's three fundamental rules of planetary motion. Those rules have been tested and confirmed so many times that astronomers now refer to them as natural laws (**How Do We Know? 4-2**). They are commonly called Kepler's laws of planetary motion (■ Table 4-1).

■ **Table 4-1** | **Kepler's Laws of Planetary Motion**

- I. The orbits of the planets are ellipses with the sun at one focus.
- II. A line from a planet to the sun sweeps over equal areas in equal intervals of time.
- III. A planet's orbital period squared is proportional to its average distance from the sun cubed:

$$P_{\text{yr}}^2 = a^3_{\text{AU}}$$

Kepler's first law says that the orbits of the planets around the sun are ellipses with the sun at one focus. Thanks to the precision of Tycho's observations and the sophistication of Kepler's mathematics, Kepler was able to recognize the elliptical shape of the orbits even though they are nearly circular. Mercury has the most elliptical orbit, but even it deviates only slightly from a circle (■ Figure 4-15).

Kepler's second law says that an imaginary line drawn from the planet to the sun always sweeps over equal areas in equal intervals of time. This means that when the planet is closer to the sun and the line connecting it to the sun is shorter, the planet moves more rapidly, and the line sweeps over the same area that is swept over when the planet is farther from the sun. You can see how the planet in Figure 4-15 would move from point A to point B in one month, sweeping over the area shown. But when the planet is farther from the sun, one month's motion would be shorter, from A' to B' ,

and the area swept out would be the same.

Kepler's third law relates a planet's orbital period to its average distance from the sun. The orbital period, P , is the time a planet takes to travel around the sun once. Its average distance from the sun turns out to equal the semimajor axis of its orbit, a . Kepler's third law says that a planet's orbital period squared is proportional to the semimajor axis of its orbit cubed. Measuring P in years and a in astronomical units, you can summarize the third law as

$$P_{\text{yr}}^2 = a^3_{\text{AU}}$$

For example, Jupiter's average distance from the sun is roughly 5.2 AU. The semimajor axis cubed is about 140, so the period must be the square root of 140, which equals just under 12 years.

Notice that Kepler's three laws are empirical. That is, they describe a phenomenon without explaining why it occurs. Kepler derived the laws from Tycho's extensive observations, not from any first principle, fundamental assumption, or theory. In fact, Kepler never knew what held the planets in their orbits or why they continued to move around the sun.

The Rudolphine Tables

Kepler continued his mathematical work on *The Rudolphine Tables*, and at last, in 1627, it was ready. He financed the printing himself, dedicating the book to the memory of Tycho Brahe. In fact, Tycho's name appears in larger type on the title page than Kepler's own. This is surprising because the tables were not based on the Tyconic system but on the heliocentric model of Copernicus and the elliptical orbits of Kepler. The reason for

Hypothesis, Theory, and Law

Why is a theory much more than just a guess? Scientists study nature by devising and testing new hypotheses and then developing the successful ideas into theories and laws that describe how nature works. A good example is the connection between sour milk and the spread of disease.

A scientist's first step in solving a natural mystery is to propose a reasonable explanation based on what is known so far. This proposal, called a **hypothesis**, is a single assertion or statement that must be tested through observation and experimentation. From the time of Aristotle philosophers believed that food spoils as a result of the spontaneous generation of life—for example, mold growing out of drying bread. French chemist Louis Pasteur (1822–1895) hypothesized that microorganisms were not spontaneously generated but were carried through the air. To test his hypothesis he sealed an uncontaminated nutrient broth in glass completely protecting it from the microorganisms on dust particles in the air. No mold grew, effectively disproving spontaneous generation. Although others had argued against spontaneous generation before Pasteur, it was Pasteur's meticulous testing of his hypothesis through experimentation that finally convinced the scientific community.

A **theory** generalizes the specific results of well-confirmed hypotheses to give a broader description of nature, which can be applied to

a wide variety of circumstances. For instance, Pasteur's specific hypothesis about mold growing in broth contributed to a broader theory that disease is caused by microorganisms transmitted from sick people to well people. This theory, called the germ theory of disease, is a cornerstone of modern medicine. It is a **Common Misconception** that the word "theory" means a tentative idea, a guess. As you have just learned, scientists actually use the word "theory" to mean an idea that is widely applicable and confirmed by abundant evidence.

Sometimes, when a theory has been refined, tested, and confirmed so often that scientists have great confidence in it, it is called a **natural law**. Natural laws are the most fundamental principles of scientific knowledge. Kepler's laws of planetary motion are good examples.

Confidence is the key. In general, scientists have more confidence in a theory than in a hypothesis and the most confidence in a natural law. However, there is no precise distinction among a hypothesis, a theory, and a law, and use of these terms is sometimes a matter of tradition. For instance, some textbooks refer to the Copernican "theory" of heliocentrism, but it had not been well tested when Copernicus proposed it, and it is more rightly called the Copernican hypothesis. At the other extreme, Darwin's "theory" of evolution,



A fossil of a 500-million-year-old trilobite: Darwin's theory of evolution has been tested many times and is universally accepted in the life sciences, but by custom it is called Darwin's theory and not Darwin's law.
(From the collection of John Coolidge III)

containing many hypotheses that have been tested and confirmed over and over for nearly 150 years, might more correctly be called a natural law.

Kepler's evident deference was Tycho's family, still powerful and still intent on protecting Tycho's reputation. They even demanded a share of the profits and the right to censor the book before publication, though they changed nothing but a few words on the title page and added an elaborate dedication to the emperor.

The Rudolphine Tables was Kepler's masterpiece. It could predict the positions of the planets 10 to 100 times more accurately than previous tables. Kepler's tables were the precise model of planetary motion that Copernicus had sought but failed to find. The accuracy of *The Rudolphine Tables* was strong evidence that both Kepler's laws of planetary motion and the Copernican hypothesis for the place of Earth were correct. Copernicus would have been pleased.

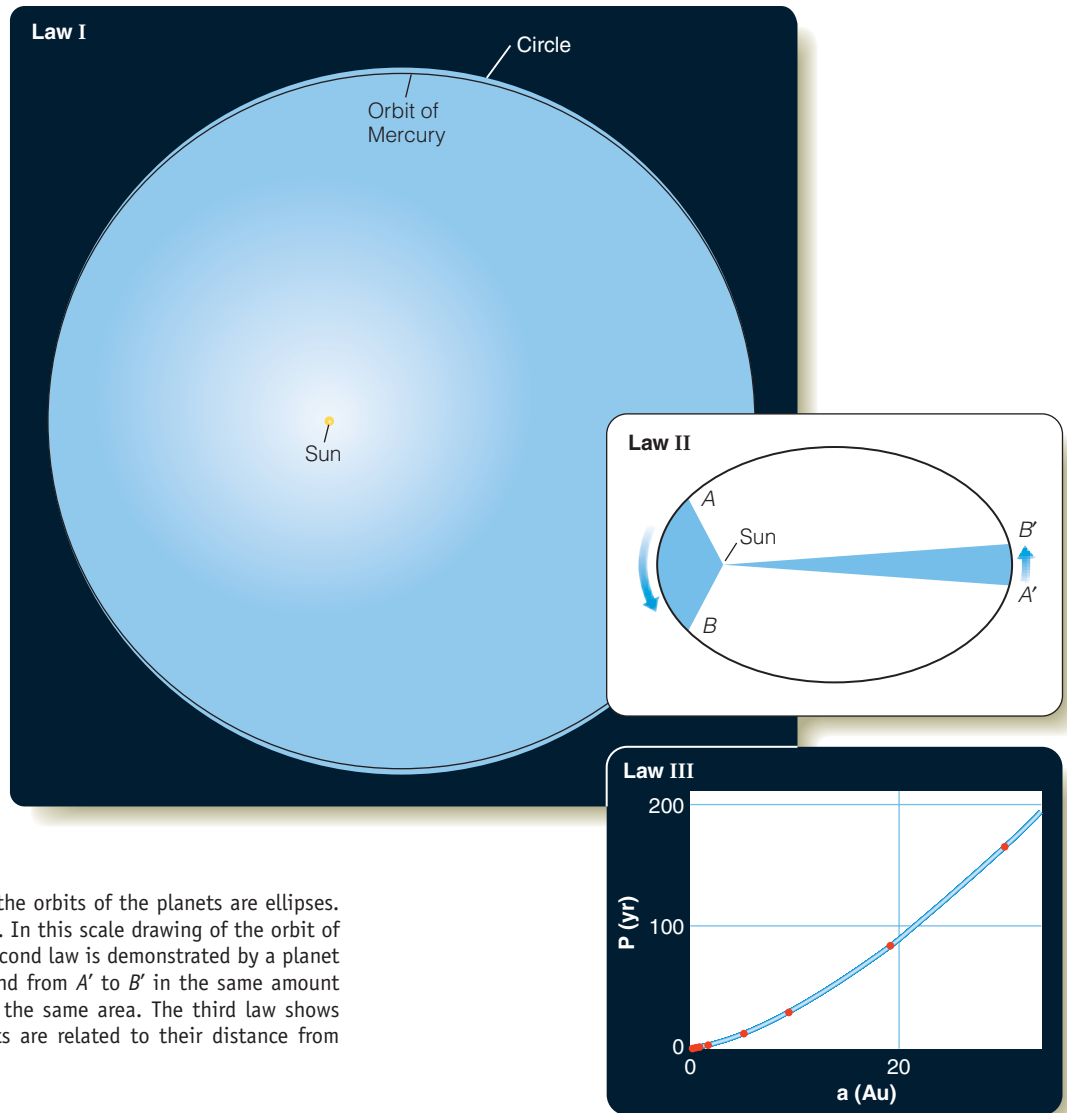
Kepler died in 1630. He had solved the problem of planetary motion, and his *Rudolphine Tables* demonstrated his solution. Although he did not understand why the planets moved or

why they followed ellipses, insights that had to wait half a century for Isaac Newton, Kepler's three laws worked. In science the only test of a theory is, "Does it describe reality?" Kepler's laws have been used for almost four centuries as a true description of orbital motion.

SCIENTIFIC ARGUMENT

How was Kepler's model with regular solids based on first principles? How were his three laws based on evidence?

When he was younger, Kepler accepted Plato's argument for the perfection of the heavens. Furthermore, Kepler argued that the five regular solids were perfect geometrical figures and should be part of the perfect heavens along with spheres. He then arranged the five regular solids to produce the approximate spacing among the spheres that carried the planets in the Copernican model. Kepler's model was thus based on a first principle—the perfection of the heavens.



■ **Figure 4-15**

Kepler's three laws: The first law says the orbits of the planets are ellipses. The orbits, however, are nearly circular. In this scale drawing of the orbit of Mercury, it looks nearly circular. The second law is demonstrated by a planet that moves from *A* to *B* in 1 month and from *A'* to *B'* in the same amount of time. The two blue segments have the same area. The third law shows that the orbital periods of the planets are related to their distance from the sun.

Much later, Kepler derived his three laws of motion from the observations made by Tycho Brahe during 20 years on Hveen. The observations were the evidence, and they gave Kepler a reality check each time he tried a new calculation. He chose ellipses because they fit the data and not because he thought ellipses had any special significance.

The Copernican model was a poor predictor of planetary motion, but *The Rudolphine Tables* was much more accurate. **What first principle did Copernicus follow that was abandoned when Kepler looked at the evidence?**

4-4 Galileo Galilei

MOST PEOPLE THINK they know two facts about Galileo, but both facts are wrong; they are **Common Misconceptions**, so you have probably heard them. Galileo did not invent the

telescope, and he was not condemned by the Inquisition for believing that Earth moved around the sun. Then why is Galileo so famous? Why did the Vatican reopen his case in 1979, almost 400 years after his trial? As you learn about Galileo, you will discover that his trial concerned not just the place of Earth and the motion of the planets but also a new and powerful method of understanding nature, a method called science.

Telescopic Observations

Galileo Galilei (■ Figure 4-16) was born in 1564 in Pisa, a city in what is now Italy, and he studied medicine at the university there. His true love, however, was mathematics, and, although he had to leave school early for financial reasons, he returned only four years later as a professor of mathematics. Three years after that he became professor of mathematics at the university at Padua, where he remained for 18 years.



■ **Figure 4-16**

Galileo, remembered as the great defender of Copernicanism, also made important discoveries in the physics of motion. He was honored here on an Italian 2000-lira note.

During this time, Galileo seems to have adopted the Copernican model, although he admitted in a 1597 letter to Kepler that he did not support Copernicanism publicly. At that time, the Copernican hypothesis was not officially considered heretical, but it was hotly debated among astronomers, and Galileo, living in a region controlled by the Church, cautiously avoided trouble. It was the telescope that finally drove Galileo to publicly defend the heliocentric model.

The telescope was apparently invented around 1608 by lens makers in Holland. Galileo, hearing descriptions in the fall of 1609, was able to build telescopes in his workshop. In fact, Galileo was not the first person to look at the sky through a telescope, but he was the first person to apply telescopic observations to the theoretical problem of the day—the place of Earth.

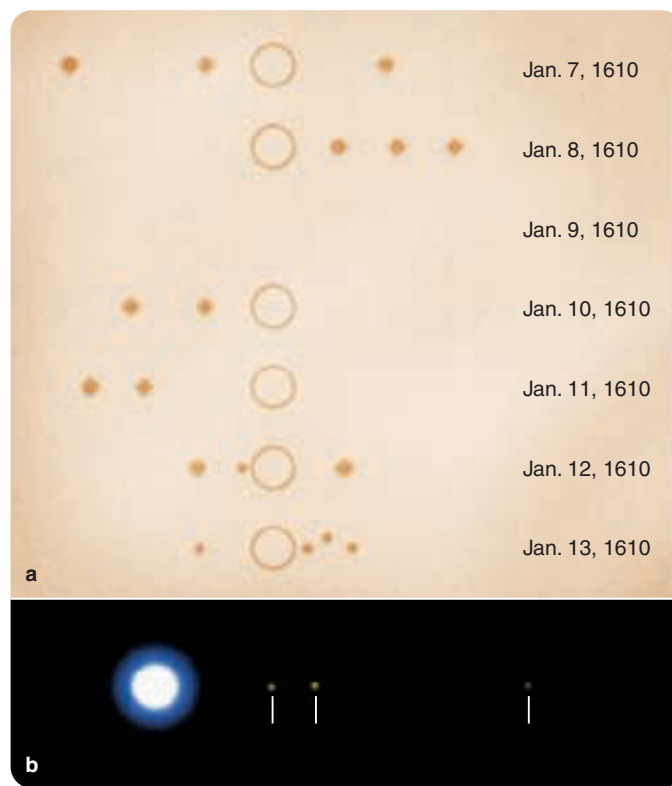
What Galileo saw through his telescopes was so amazing that he rushed a small book into print. *Sidereus Nuncius* (*The Sidereal Messenger*) reported three major discoveries. First, the moon was not perfect. It had mountains and valleys on its surface, and Galileo even used some of the mountains' shadows to calculate their height. Aristotle's philosophy held that the moon was perfect, but Galileo showed that it was not only imperfect but was a world with features like Earth's.

The second discovery reported in the book was that the Milky Way was made up of myriad stars too faint to see with the unaided eye. While intriguing, this could not match Galileo's third discovery. Galileo's telescope revealed four new “planets” circling Jupiter, objects known today as the **Galilean moons** of Jupiter (■ Figure 4-17).

The moons of Jupiter were strong evidence for the Copernican model. Critics of Copernicus had said Earth could not move because the moon would be left behind, but Galileo's discovery

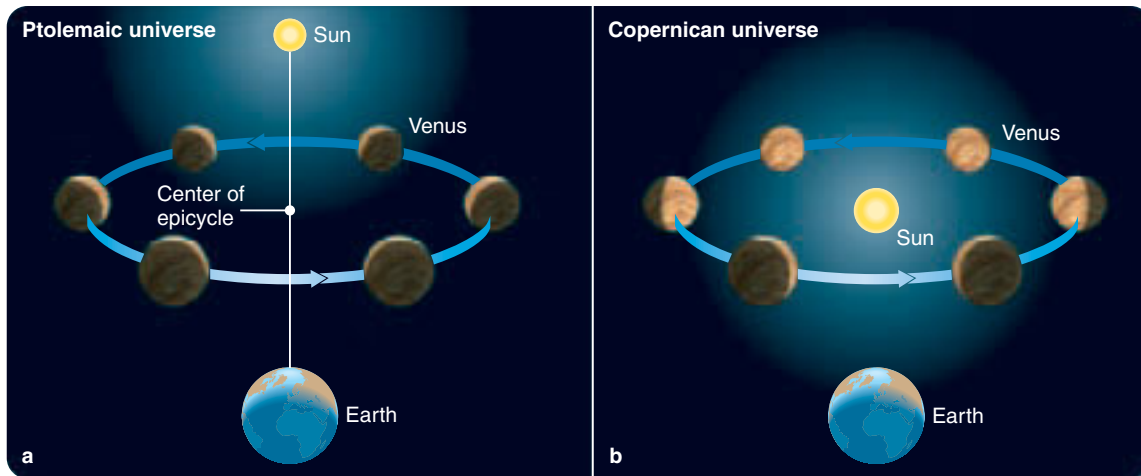
showed that Jupiter, which everyone agreed was moving, was able to keep its satellites. That suggested that Earth, too, could move and keep its moon. Aristotle's philosophy also included the belief that all heavenly motion was centered on Earth. Galileo's observations showed that Jupiter's moons revolve around Jupiter, suggesting that there could be other centers of motion besides Earth.

Some time after *Sidereus Nuncius* was published, Galileo noticed something else that made Jupiter's moons even stronger evidence for the Copernican model. When he measured the orbital periods of the four moons, he found that the innermost moon had the shortest period and that the moons farther from Jupiter had proportionally longer periods. Jupiter's moons made up a harmonious system ruled by Jupiter, just as the planets in the Copernican universe were a harmonious system ruled by the sun.



■ **Figure 4-17**

(a) On the night of January 7, 1610, Galileo saw three small “stars” near the bright disk of Jupiter and sketched them in his notebook. On subsequent nights (excepting January 9, which was cloudy), he saw that the stars were actually four moons orbiting Jupiter. (b) This photo taken through a modern telescope shows the overexposed disk of Jupiter and three of the four Galilean moons. (Grundy Observatory)



■ **Figure 4-18**

(a) If Venus moved in an epicycle centered on the Earth-sun line (see page 57), it would always appear as a crescent.
 (b) Galileo's telescope showed that Venus goes through a full set of phases, proving that it must orbit the sun.

(See Figure 4-10b.) The similarity isn't proof, but Galileo saw it as an argument that the solar system could be sun centered rather than Earth centered.

In the years following publication of *Sidereus Nuncius*, Galileo made two additional discoveries. When he observed the sun, he discovered sunspots, raising the suspicion that the sun was less than perfect. Further, by noting the movement of the spots, he concluded that the sun was a sphere and that it rotated on its axis.

His most dramatic discovery came when he observed Venus. Galileo saw that it was going through phases like those of the moon. In the Ptolemaic model, Venus moves around an epicycle centered on a line between Earth and the sun. That means it would always be seen as a crescent (■ Figure 4-18a). But Galileo saw Venus go through a complete set of phases, which proved that it did indeed revolve around the sun (Figure 4-18b). There is no way the Ptolemaic model could produce those phases. This was the strongest evidence that came from Galileo's telescope; but, when controversy erupted, it focused more on the perfection of the sun and moon and the motion of the satellites of Jupiter.

Sidereus Nuncius was very popular and made Galileo famous. He became chief mathematician and philosopher to the Grand Duke of Tuscany in Florence. In 1611, Galileo visited Rome and was treated with great respect. He had long, friendly discussions with the powerful Cardinal Barberini, but he also made enemies. Personally, Galileo was outspoken, forceful, and sometimes tactless. He enjoyed debate, but most of all he enjoyed being right. In lectures, debates, and letters he offended important people who questioned his telescopic discoveries.

By 1616, Galileo was the center of a storm of controversy. Some critics said he was wrong, and others said he was lying. Some refused to look through a telescope lest it mislead them,



■ **Figure 4-19**

Galileo's telescope made him famous, and he demonstrated his telescope and discussed his observations with powerful people. Some thought the telescope was the work of the devil and would deceive anyone who looked. In any case, Galileo's discoveries produced intense and, in some cases, angry debate. (Yerkes Observatory)

and others looked and claimed to see nothing (hardly surprising, given the awkwardness of those first telescopes) (■ Figure 4-19). Pope Paul V decided to end the disruption, so when Galileo visited Rome in 1616 Cardinal Bellarmine interviewed him privately and ordered him to cease debate. There is some controversy today about the nature of Galileo's instructions, but he did not pursue astronomy for some years after the interview. Books

relevant to Copernicanism were banned in all Catholic lands, although *De Revolutionibus*, recognized as an important and useful book in astronomy, was only suspended pending revision. Everyone who owned a copy of the book was required to cross out certain statements and add handwritten corrections stating that Earth's motion and the central location of the sun were only theories and not facts.

Dialogo and Trial

In 1621 Pope Paul V died, and his successor, Pope Gregory XV, died in 1623. The next pope was Galileo's friend Cardinal Barberini, who took the name Urban VIII. Galileo rushed to Rome hoping to have the prohibition of 1616 lifted; and, although the new pope did not revoke the orders, he did apparently encourage Galileo. Soon after returning home, Galileo began to write his great defense of Copernicanism, finally completing it at the end of 1629. After some delay, the book was approved by both the local censor in Florence and the head censor of the Vatican in Rome. It was printed in February 1632.

Called *Dialogo Sopra i Due Massimi del Mondo (Dialogue Concerning the Two Chief World Systems)*, it confronts the ancient astronomy of Aristotle and Ptolemy with the Copernican model and with telescopic observations as evidence. Galileo wrote the book in the form of a debate among three friends. Salviati, a swift-tongued defender of Copernicus, dominates the book; Sagredo is intelligent but largely uninformed. Simplicio, the dismal defender of Ptolemy, makes all the old arguments and sometimes doesn't seem very bright.

The publication of *Dialogo* created a storm of controversy, and it was sold out by August 1632, when the Inquisition ordered sales stopped. The book was a clear defense of Copernicus, and, probably unintentionally, Galileo exposed the pope's authority to ridicule. Urban VIII was fond of arguing that, as God was omnipotent, He could construct the universe in any form while making it appear to humans to have a different form, and thus its true nature could not be deduced by mere observation. Galileo placed the pope's argument in the mouth of Simplicio, and Galileo's enemies showed the passage to the pope as an example of Galileo's disrespect. The pope thereupon ordered Galileo to face the Inquisition.

Galileo was interrogated by the Inquisition four times and was threatened with torture. He must have thought often of Giordano Bruno, a philosopher, poet, and Dominican monk, who was tried, condemned, and burned at the stake in Rome in 1600. One of Bruno's offenses had been Copernicanism. However, Galileo's trial did not center on his belief in Copernicanism. *Dialogo* had been approved by two censors. Rather, the trial centered on the instructions given Galileo in 1616. From his file in the Vatican, his accusers produced a record of the meeting between Galileo and Cardinal Bellarmine

that included the statement that Galileo was "not to hold, teach, or defend in any way" the principles of Copernicus. Some historians believe that this document, which was signed neither by Galileo nor by Bellarmine nor by a legal secretary, was a forgery. Others suspect it may be a draft that was never used. It is quite possible that Galileo's actual instructions were much less restrictive; but, in any case, Bellarmine was dead and could not testify at Galileo's trial.

The Inquisition condemned Galileo not for heresy but for disobeying the orders given him in 1616. On June 22, 1633, at the age of 70, kneeling before the Inquisition, Galileo read a recantation admitting his errors. Tradition has it that as he rose he whispered "*E pur si muove*" ("Still it moves"), referring to Earth.

Although he was sentenced to life imprisonment, he was, perhaps through the intervention of the pope, confined at his villa for the next ten years. He died there on January 8, 1642, 99 years after the death of Copernicus.

Galileo was not condemned for heresy, nor was the Inquisition interested when he tried to defend Copernicanism. He was tried and condemned on a charge you might call a technicality. Nevertheless, in his recantation he was forced to abandon all belief in heliocentrism. His trial has been held up as an example of the suppression of free speech and free inquiry and as a famous attempt to deny reality. Some of the world's greatest authors, including Bertolt Brecht, have written about Galileo's trial. That is why Pope John Paul II created a commission in 1979 to reexamine the case against Galileo.

To understand the trial, you must recognize that it was the result of a conflict between two ways of understanding the universe. Since the Middle Ages, biblical scholars had taught that the only path to true understanding was through religious faith. St. Augustine (AD 354–430) wrote "*Credo ut intelligame*," which can be translated as "Believe in order to understand." Galileo and other scientists of the Renaissance, however, used their own observations as evidence to try to understand nature. When their observations contradicted Scripture, they assumed that it was their observations that truly represented reality. Galileo paraphrased Cardinal Baronius in saying, "The Bible tells us how to go to heaven, not how the heavens go." The trial of Galileo was not really about the place of Earth in the universe. It was not about Copernicanism. It wasn't even about the instructions Galileo received in 1616. It was, in a larger sense, about the birth of modern science as a rational way to understand the universe (■ Figure 4-20).

The commission appointed by John Paul II in 1979, reporting its conclusions in October 1992, said of Galileo's inquisitors, "This subjective error of judgment, so clear to us today, led them to a disciplinary measure from which Galileo 'had much to suffer.'" Galileo was not found innocent in 1992 so much as the Inquisition was forgiven for having charged him in the first place.

■ **Figure 4-20**

Although he did not invent it, Galileo will always be associated with the telescope because it was the source of the observational evidence he used to try to understand the universe. By depending on observation of reality instead of first principles of philosophy and theology, Galileo led the way to the invention of modern science as a way to know about the natural world.



SCIENTIFIC ARGUMENT

How were Galileo's observations of the moons of Jupiter evidence against the Ptolemaic model?

Scientific arguments are based on evidence, and reasoning from evidence was Galileo's fundamental way of knowing about the heavens. Galileo presented his arguments in the form of evidence and conclusions, and the moons of Jupiter were key evidence. Ptolemaic astronomers argued that Earth could not move or it would lose its moon, but even in the Ptolemaic universe Jupiter moved, and the telescope showed that it had moons and kept them. Evidently, Earth could move and not leave its moon behind. Furthermore, moons circling Jupiter did not fit the classical belief that all motion was centered on Earth. Obviously there could be other centers of motion. Finally, the orbital periods of the moons were related to their distance from Jupiter, just as the orbital periods of the planets were, in the Copernican system, related to their distance from the sun. This similarity suggested that the sun rules its harmonious family of planets just as Jupiter rules its harmonious family of moons.

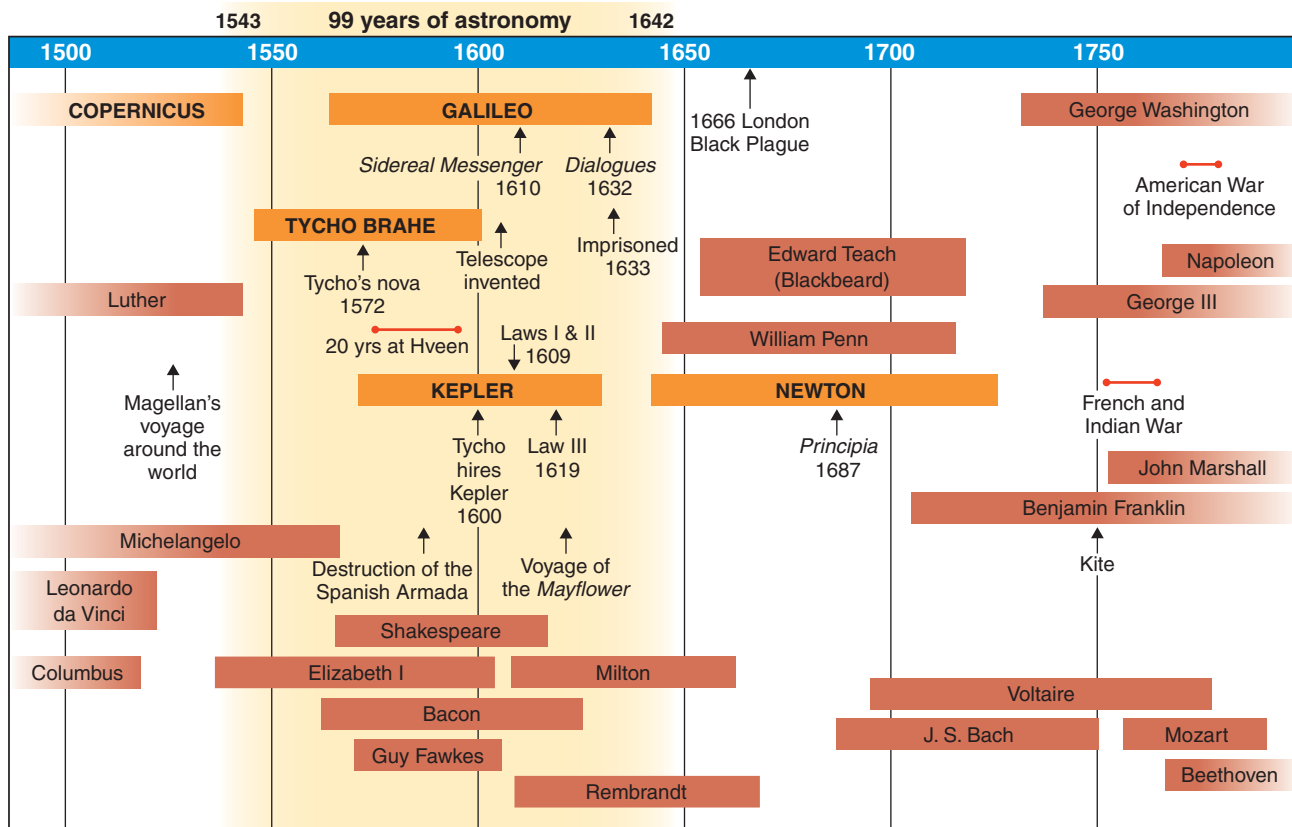
Of all of Galileo's telescopic observations, the moons of Jupiter caused the most debate, but the craters on the moon and the phases of Venus were also critical evidence. Build an argument to discuss that evidence. **How did craters on the moon and the phases of Venus argue against the Ptolemaic model?**

4-5 Modern Astronomy

THE SCIENCE KNOWN AS MODERN ASTRONOMY began during the 99 years between the deaths of Copernicus and Galileo (1543 to 1642). It was an age of transition that marked the change from the Ptolemaic model of the universe to the Copernican model with the attendant controversy over the place of the Earth. But that same period also marked a transition in the nature of astronomy in particular and of science in general, a transition illustrated in the solution of the puzzle of planetary motion. The puzzle was not solved by philosophical arguments about the perfection of the heavens or by debate over the meaning of scripture. It was solved by precise observation and careful computation, techniques that are the foundation of modern science.

The discoveries made by Kepler and Galileo found acceptance in the 1600s because the world was in transition. Astronomy was not the only thing changing during this period. The Renaissance is commonly taken to be the period between 1300 and 1600, and these 99 years of astronomical history lie at the culmination of the reawakening of learning in all fields (■ Figure 4-21). Ships were sailing to new lands and encountering new cultures. The world was open to new ideas and new observations. Martin Luther reformed the Christian religion, and other philosophers and scholars rethought their areas of human knowledge. Had Copernicus not published his hypothesis, someone else would have suggested that the universe is heliocentric. History was ready to shed the Ptolemaic system.

This period marks the beginning of the modern scientific method. Beginning with Copernicus, scientists such as Tycho, Kepler, and Galileo depended more and more on evidence, observation, and measurement rather than on first principles. This, too, is coupled to the Renaissance and its advances in metalworking and lens making. At the time of Copernicus, no astronomer had looked through a telescope, because one could not be made. By 1642, not only telescopes but also other sensitive measuring instruments had transformed science into something new and precise. As you can imagine, scientists were excited by these discoveries, and they founded scientific societies that increased the exchange of observations and hypotheses and stimulated more and better work. The most important advance, however, was the application of mathematics to scientific questions. Kepler's work demonstrated the power of mathematical analysis; and, as the quality of these numerical techniques improved, the progress of science accelerated. This story of the birth of modern astronomy is actually the story of the birth of modern science as well.



■ **Figure 4-21**

The 99 years between the death of Copernicus in 1543 and the death of Galileo in 1642 marked the transition from the ancient astronomy of Ptolemy and Aristotle to the revolutionary theory of Copernicus and, simultaneously, the invention of science as a way of understanding nature.

What Are We? Participants

The scientific revolution began when Copernicus made humanity part of the universe. Before Copernicus, people thought of Earth as a special place different from any of the objects in the sky; but, in trying to explain the motions in the sky, Copernicus made Earth one of the planets. Galileo and those who brought him to trial understood the significance of making Earth a planet. It made Earth and humanity part of the universe, part of nature.

Kepler showed that the planets move according to simple rules. We are not in a special place ruled by mysterious planetary forces. Earth, the sun, and all of humanity are part of a universe whose motions can be described by a few fundamental laws. If simple laws describe the motions of the planets, then the universe is not ruled by mysterious influences as in astrology or the whims of the gods atop Mount Olympus. And if the universe can be described by simple rules, then it is open to scientific study.

Before Copernicus, people felt they were special because they thought they were at the center of the universe. Copernicus, Kepler, and Galileo showed that we are not at the center but are part of an elegant and complex universe. Astronomy tells us that we are special because we can study the universe and eventually understand what we are. But it also tells us that we are not just observers of nature; we are participants.

Study and Review

Summary

- ▶ **Archaeoastronomy (p. 50)** is the study of the astronomy of ancient peoples. Many cultures around the world observed the sky and marked important alignments. Structures such as Stonehenge, Newgrange, and the Sun Dagger have astronomical alignments. In most cases, ancient cultures, having no written language, left no detailed records of their astronomical beliefs.
- ▶ Greek astronomy, derived in part from Babylon and Egypt, is better known because written documents have survived.
- ▶ Classical philosophers accepted as a first principle that Earth was the unmoving center of the universe. Another first principle was that the heavens were perfect, so philosophers such as Plato argued that, because the sphere was the most perfect geometrical form, the heavens must be made up of spheres in uniform rotation. This led to the belief in **uniform circular motion (p. 53)**.
- ▶ Many astronomers argued that Earth could not be moving because they could see no **parallax (p. 56)** in the positions of the stars.
- ▶ Aristotle's estimate for the size of Earth was only about one-third of its true size. Eratosthenes used the well at Syene to measure the diameter of Earth and got an accurate estimate.
- ▶ The **geocentric universe (p. 54)** became part of the teachings of the great philosopher Aristotle, who argued that the sun, moon, and stars were carried around Earth on rotating crystalline spheres.
- ▶ Hipparchus, who lived about two centuries after Aristotle, devised a model in which the sun, moon, and planets revolved in circles called **eccentrics (p. 55)** with Earth near but not precisely at their centers.
- ▶ **Retrograde motion (p. 56)**, the occasional westward (backward) motion of the planets, was difficult for astronomers to explain.
- ▶ About AD 140, Aristotle's model was given mathematical form in Claudius Ptolemy's book *Almagest*. Ptolemy preserved the principles of geocentrism and uniform circular motion, but he added **epicycles (p. 57)**, **deferents (p. 57)**, and **equants (p. 57)**. Ptolemy's epicycles could approximate retrograde motion, but the Ptolemaic model was not very accurate, and it had to be revised a number of times as centuries passed.
- ▶ Copernicus devised a **heliocentric universe (p. 58)**. He preserved the principle of uniform circular motion, but he argued that Earth rotates on its axis and revolves around the sun once a year. His theory was controversial because it contradicted Church teaching. He published his theory in his book *De Revolutionibus* in 1543, the same year he died.
- ▶ A **hypothesis (p. 66)** is a specific statement about nature that needs further testing, but a **theory (p. 66)** is usually a general description of some aspect of nature that has been tested. Some theories are very well understood and widely accepted. A **natural law (p. 66)** is a fundamental principle in which scientists have great confidence.
- ▶ Because Copernicus kept uniform circular motion as part of his theory, his model did not predict the motions of the planets well, but it did offer a simple explanation of retrograde motion without using big epicycles.
- ▶ One reason the Copernican model won converts was that it was more elegant. Venus and Mercury were treated the same as all the other planets, and the velocity of each planet was related to its distance from the sun.
- ▶ The shift from the geocentric **paradigm (p. 61)** to the heliocentric paradigm is an example of a scientific revolution.
- ▶ Although Tycho Brahe developed his own model in which the sun and moon circled Earth and the planets circled the sun, his great contribution was to compile detailed observations of the positions of the sun, moon, and planets over a period of 20 years, observations that were later used by Kepler.
- ▶ Kepler inherited Tycho's books of observations in 1601 and used them to discover three laws of planetary motion. He found that the planets follow **ellipses (p. 64)** with the sun at one focus, that they move faster when near the sun, and that a planet's orbital period squared is proportional to the **semimajor axis, a (p. 64)**, of its orbit cubed.
- ▶ The **eccentricity, e (p. 64)**, of an orbit is a measure of its departure from a perfect circle. A circle is an ellipse with an eccentricity of zero.
- ▶ Kepler's final book, *The Rudolphine Tables* (1627), combined heliocentrism with elliptical orbits and predicted the positions of the planets well.
- ▶ Galileo used the newly invented telescope to observe the heavens, and he recognized the significance of what he saw there. His discoveries of the phases of Venus, the satellites of Jupiter now known as the **Galilean moons (p. 68)**, the mountains of Earth's moon, and other phenomena helped undermine the Ptolemaic universe.
- ▶ Galileo based his analysis on observational evidence. In 1633, he was condemned by the Inquisition for disobeying instructions not to hold, teach, or defend Copernicanism.
- ▶ Historians of science view Galileo's trial as a conflict between two ways of knowing about nature, reasoning from first principles and depending on evidence.
- ▶ The 99 years from the death of Copernicus to the death of Galileo marked the birth of modern science. From that time on, science depended on evidence to test theories and relied on the mathematical analytic methods first demonstrated by Kepler.

Review Questions

1. What evidence is there that early human cultures observed astronomical phenomena?
2. Why did Plato propose that all heavenly motion was uniform and circular?
3. In Ptolemy's model, how do the epicycles of Mercury and Venus differ from those of Mars, Jupiter, and Saturn?
4. Why did Copernicus have to keep small epicycles in his model?
5. When Tycho observed the new star of 1572, he could detect no parallax. Why did that result undermine belief in the Ptolemaic system?
6. Does Tycho's model of the universe explain the phases of Venus that Galileo observed? Why or why not?
7. How do the first two of Kepler's three laws overthrow one of the basic beliefs of classical astronomy?
8. How did *The Alfonsine Tables*, *The Prutenic Tables*, and *The Rudolphine Tables* differ?
9. Explain how each of Galileo's telescopic discoveries contradicted the Ptolemaic theory.
10. Galileo was condemned, but Kepler, also a Copernican, was not. Why not?
11. **How Do We Know?** What is a paradigm, and how is it related to a scientific revolution?
12. **How Do We Know?** How would you describe the difference between a hypothesis, a theory, and a law?

Discussion Questions

1. Historian of science Thomas Kuhn has said that *De Revolutionibus* was a revolution-making book but not a revolutionary book. How was it an old-fashioned, classical book?
2. Why might Tycho Brahe have hesitated to hire Kepler? Why do you suppose he appointed Kepler his scientific heir?
3. How does the modern controversy over creationism and evolution reflect two ways of knowing about the physical world?

Problems

1. Draw and label a diagram of the eastern horizon from northeast to southeast and label the rising point of the sun at the solstices and equinoxes. (See page 19 and Figure 4-1.)
2. If you lived on Mars, which planets would exhibit retrograde motion? Which would never be visible as crescent phases?
3. If a planet has an average distance from the sun of 4 AU, what is its orbital period?
4. If a space probe is sent into an orbit around the sun that brings it as close as 0.5 AU and as far away as 5.5 AU, what will be its orbital period?
5. Neptune orbits the sun with a period of 164.8 years. What is its average distance from the sun?
6. Galileo's telescope showed him that Venus has a large angular diameter (61 arc seconds) when it is a crescent and a small angular diameter (10 arc seconds) when it is nearly full. Use the small-angle formula to find the ratio of its maximum distance to its minimum distance. Is this ratio compatible with the Ptolemaic universe shown on page 57?

7. Galileo's telescopes were not of high quality by modern standards. He was able to see the moons of Jupiter, but he never reported seeing features on Mars. Use the small-angle formula to find the angular diameter of Mars when it is closest to Earth. How does that compare with the maximum angular diameter of Jupiter?

Learning to Look

1. Study Figure 4-11 and describe the phases that Venus would have displayed to Galileo's telescope if the Tychonic universe had been correct.
2. What three astronomical objects are represented here? What are the two rings?



3. Use the figure below to explain how the Ptolemaic model treated some planets differently from the rest. How did the Copernican model treat all of the planets the same?



5

Gravity



Guidepost

If only Renaissance astronomers had understood gravity, they wouldn't have had so much trouble describing the motion of the planets, but that insight didn't appear until three decades after the trial of Galileo. Isaac Newton started from the work of Galileo and devised a way to explain motion and gravity that allowed astronomers to understand orbits and tides. Later, in the early 20th century, Albert Einstein found an even better way to describe gravity.

This chapter is about gravity, the master of the universe. Here you will find answers to five essential questions:

- **What happens when an object falls?**
- **How did Newton discover gravity?**
- **How does gravity explain orbital motion?**
- **How does gravity explain tides?**
- **How did Einstein better describe motion and gravity?**

Gravity rules. The moon orbiting Earth, matter falling into black holes, and the overall structure of the universe are dominated by gravity. As you study gravity, you will see science in action.

Isaac Newton, shown here, could explain orbital motion using gravity.

*Nature and Nature's laws lay hid in night:
God said, "Let Newton be!" and all was
light.*

— ALEXANDER POPE

ISN'T IT WEIRD that Isaac Newton is said to have “discovered” gravity in the late 17th century—as if people didn't have gravity before that, as if they floated around holding onto tree branches? Of course, everyone experienced gravity without noticing it. Newton's insight was to see gravity as a force that both makes things fall, and keeps moons and planets in their orbits, and that realization changed the way people thought about nature (■ Figure 5-1).

5-1 Galileo and Newton

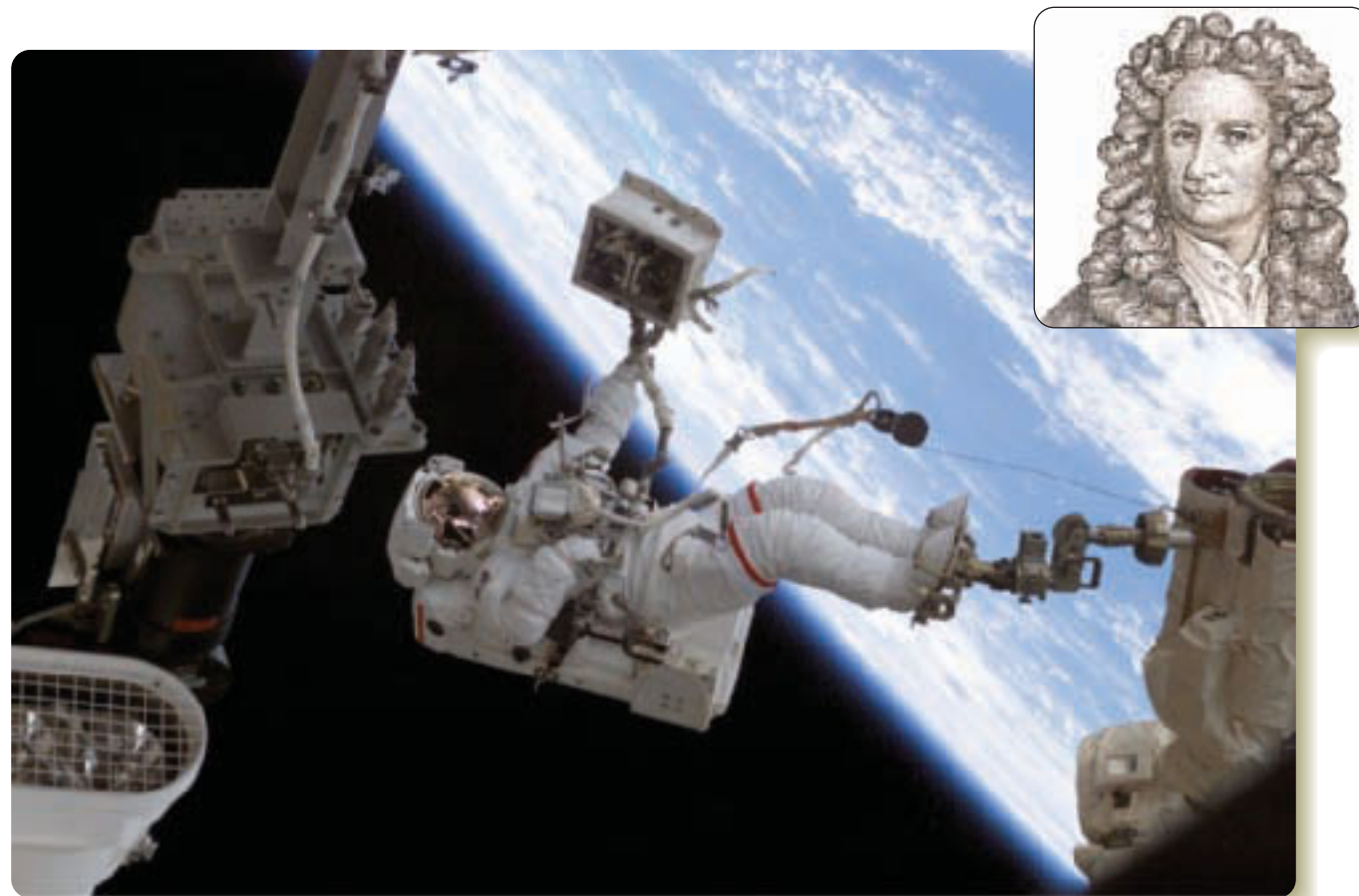
ISAAC NEWTON WAS BORN in Woolsthorpe, England, on December 25, 1642, and on January 4, 1643. This was not a biological anomaly but a calendrical quirk. Most of Europe, following the

lead of the Catholic countries, had adopted the Gregorian calendar, but Protestant England continued to use the Julian calendar. So December 25 in England was January 4 in Europe. If you use the English date, then Newton was born in the same year that Galileo Galilei died.

Newton became one of the greatest scientists who ever lived, but even he admitted the debt he owed to those who had studied nature before him. He said, “If I have seen farther than other men, it is because I stood on the shoulders of giants.” In the previous chapter, you learned about Galileo as the defender of Copernicanism who made the first use of an astronomical telescope, but he also was the first scientist who carefully studied the motions of falling bodies. That was the key information that led Newton to understand gravity.

Galileo and Motion

Galileo (■ Figure 5-2) began studying the motion of freely moving bodies even before he built his first telescope. After the Inquisition condemned and imprisoned him in 1633, he continued his study of motion. He seems to have realized that he would



■ **Figure 5-1**

Space stations and astronauts, as well as planets, moons, stars, and galaxies, follow paths called orbits that are described by three simple laws of motion and a theory of gravity first understood by Isaac Newton (1642–1727). Newtonian physics is adequate to send astronauts to the moon and to analyze the rotation of the largest galaxies. (NASA)



■ **Figure 5-2**

Although Galileo is often associated with the telescope, as on this Italian stamp, he also made systematic studies of the motion of falling bodies and made discoveries that led to the law of inertia.

have to understand motion before he could truly understand the Copernican system.

In addition to writing about a geocentric universe, Aristotle also wrote about the nature of motion, and those ideas still held sway in Galileo's time. Aristotle said that the world is made up of four classical elements: earth, water, air, and fire, each located in its proper place. The proper place for earth (meaning soil and rock) is the center of the universe, and the proper place of water is just above earth. Air and then fire form higher layers, and above them lies the realm of the planets and stars. (You can see the four layers of the classical elements in the diagram at the top of page 56.) The four elements were believed to have a natural tendency to move toward their proper place in the cosmos. Things made up mostly of air or fire—smoke, for instance—tend to move upward. Things composed mostly of earth and water—wood, rock, flesh, bone, and so on—tend to move downward. According to Aristotle, objects fall downward because they are moving toward their proper place.*

Aristotle called these motions **natural motions** to distinguish them from the **violent motions** that are produced when, for instance, you push on an object and make it move other than toward its proper place. According to Aristotle, such motions stop as soon as the force is removed. To explain how an arrow could continue to move upward even after it had left the bowstring, he said currents in the air around the arrow carried it forward even though the bowstring was no longer pushing it.

In Galileo's time and for the two preceding millennia, scholars had tended to resolve problems by referring to authority. To analyze the flight of a cannonball, for instance, they would turn to the writings of Aristotle and other classical philosophers and try to deduce what those philosophers would have said on the subject. This generated a great deal of discussion but little real progress. Galileo broke with this tradition when he conducted his own experiments.

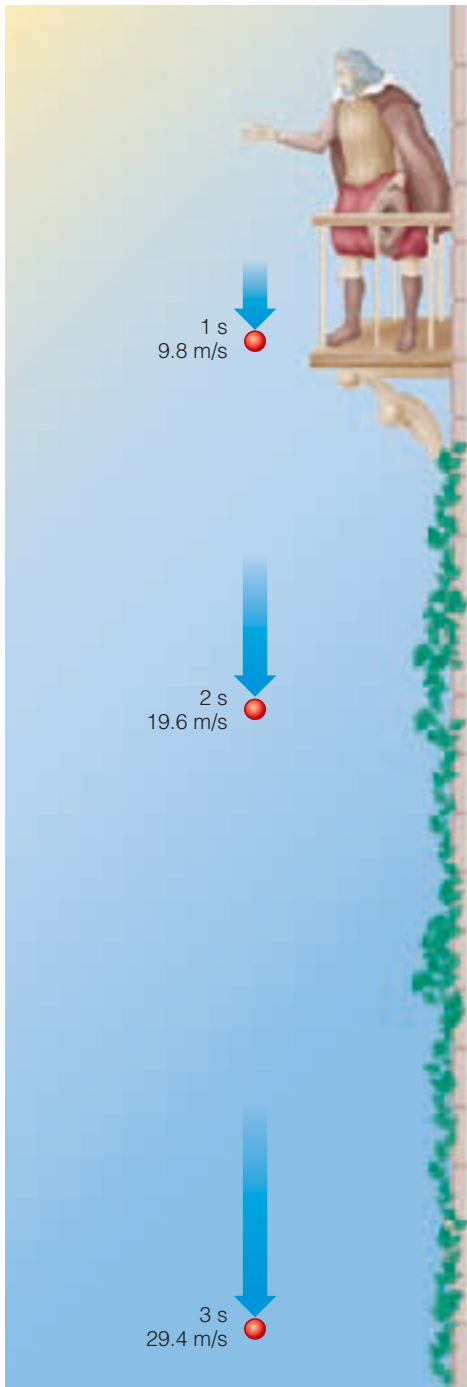
*This is one reason why Aristotle had to have a geocentric universe. If Earth's center had not also been the center of the cosmos, his explanation of gravity would not have worked.

He began by studying the motions of falling bodies, but he quickly discovered that the velocities were so great and the times so short that he could not measure them accurately. Consequently, he began using polished bronze balls rolling down gently sloping inclines. In that instance, the velocities are lower, and the times are longer. Using an ingenious water clock, he was able to measure the time the balls took to roll given distances down the incline, and he correctly recognized that these times are proportional to the times he would have measured using falling bodies.

Galileo found that falling bodies do not fall at constant rates, as Aristotle had said, but are accelerated. That is, they move faster with each passing second. Near Earth's surface, a falling object will have a velocity of 9.8 m/s (32 ft/s) at the end of 1 second, 19.6 m/s (64 ft/s) after 2 seconds, 29.4 m/s (96 ft/s) after 3 seconds, and so on. Each passing second adds 9.8 m/s (32 ft/s) to the object's velocity (■ Figure 5-3). In modern terms, this steady increase in the velocity of a falling body by 9.8 m/s each second (usually written 9.8 m/s^2) is called the **acceleration of gravity** at Earth's surface.

Galileo also discovered that the acceleration does not depend on the weight of the object. This, too, is contrary to the teachings of Aristotle, who believed that heavy objects, containing more earth and water, fell with higher velocity. Galileo found that the acceleration of a falling body is the same whether it is heavy or light. According to some accounts, he demonstrated this by dropping balls of iron and wood from the top of the Leaning Tower of Pisa to show that they would fall together and hit the ground at the same time (■ Figure 5-4a). In fact, he probably didn't perform this experiment. It would not have been conclusive anyway because of air resistance. More than 300 years later, Apollo 15 astronaut David Scott, standing on the airless moon, demonstrated the truth of Galileo's discovery by simultaneously dropping a feather and a steel geologist's hammer. They fell at the same rate and hit the lunar surface at the same time (Figure 5-4b).

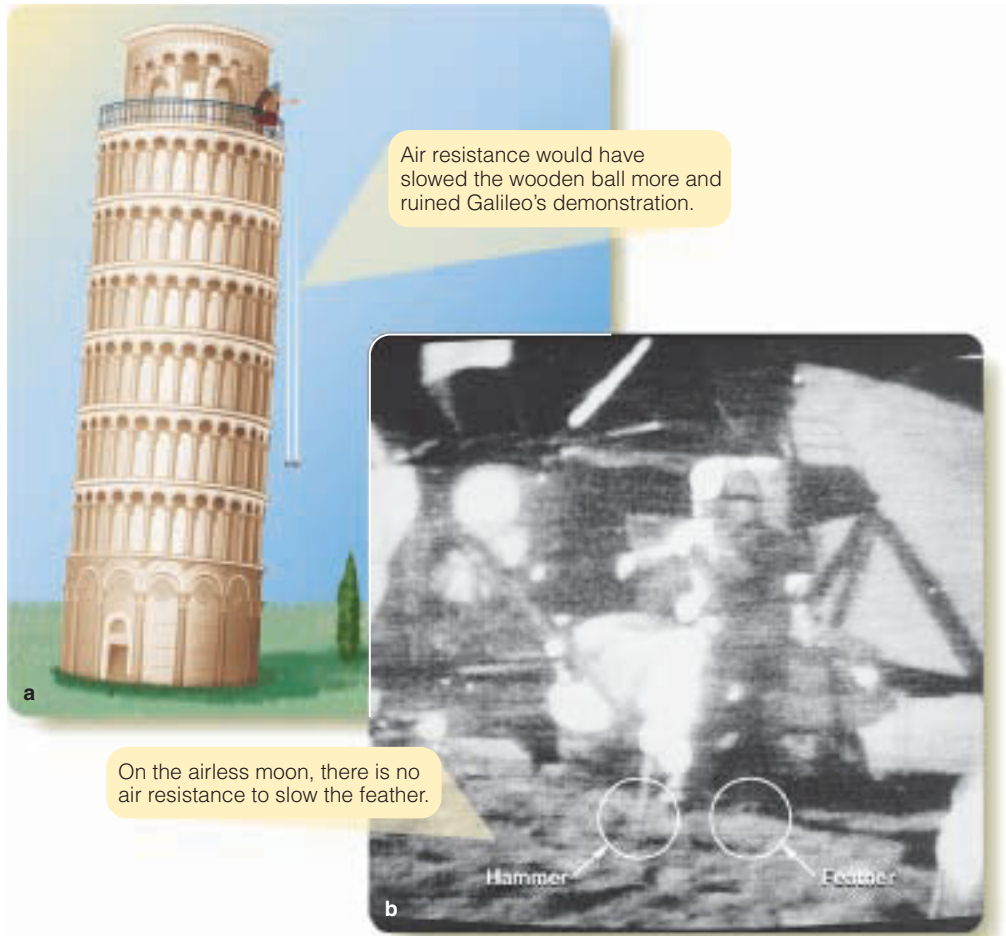
Having described natural motion, Galileo turned his attention to violent motion—that is, motion directed other than toward an object's proper place in the cosmos. Aristotle said that such motion must be sustained by a cause. We would say “a cause” today. Galileo pointed out that an object rolling down an incline is accelerated and that an object rolling up the same incline is decelerated. If the incline were perfectly horizontal and frictionless, he reasoned, there could be no acceleration or deceleration to change the object's velocity, and, in the absence of friction, the object would continue to move forever. In his own words, “any velocity once imparted to a moving body will be rigidly maintained as long as the external causes of acceleration or retardation are removed.” Motion need not be sustained by a cause, said Galileo. Once begun, motion continues until something changes it. In fact, Galileo's statement is a perfectly valid summary of the law of inertia, which became Newton's first law of motion.



■ **Figure 5-3**

Galileo found that a falling object is accelerated downward. Each second, its velocity increases by 9.8 m/s (32 ft/s).

Galileo published his work on motion in 1638, two years after he had become entirely blind and only four years before his death. The book was called *Mathematical Discourses and Demonstrations Concerning Two New Sciences, Relating to Mechanics and to Local Motion*. It is known today as *Two New Sciences*.



■ **Figure 5-4**

(a) According to tradition, Galileo demonstrated that the acceleration of a falling body is independent of its weight by dropping balls of iron and wood from the Leaning Tower of Pisa. In fact, air resistance would have confused the result. (b) In a historic television broadcast from the moon on August 2, 1971, David Scott dropped a hammer and a feather at the same instant. They fell with the same acceleration and hit the surface together. (NASA)

The book is a brilliant achievement for a number of reasons. To understand motion, Galileo had to abandon the authority of the ancients, devise his own experiments, and draw his own conclusions. In a sense, this was the first example of experimental science. But Galileo also had to generalize his experiments to discover how nature worked. Though his apparatus was finite and his results skewed by friction, he was able to imagine an infinite, frictionless plane on which a body moves at constant velocity. In his workshop, the law of inertia was obscure, but in his imagination it was clear and precise.

Newton and the Laws of Motion

From the work of Galileo, Kepler, and other early scientists, Isaac Newton was able to deduce three laws of motion (■ Table 5-1) that describe any moving object, from an automobile driving along a highway to galaxies colliding with each other. Those laws led Newton to an understanding of gravity.

Mass

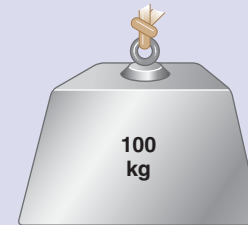
One of the most fundamental parameters in science is **mass**, a measure of the amount of matter in an object. A bowling ball, for example, contains a large amount of matter and so is more massive than a child's rubber ball of the same size.

Mass is not the same as weight. Your weight is the force that Earth's gravity exerts on the mass of your body. Because gravity pulls you downward, you press against the bathroom scale, and you can measure your weight. Floating in space, you would have no weight at all; a bathroom scale would be useless. But your body would still contain the same amount of matter, so you would still have the same mass you do on Earth.

Sports analogies illustrate the importance of mass in dramatic ways. A bowling ball, for example, must be massive to have a large effect on the pins it strikes. Imagine trying to knock down all the pins with a balloon instead of a bowling ball. In space, where the bowling ball would be weightless, a bowling ball would still have more effect on the pins than a balloon would. On the other hand, runners want track shoes that have low mass so that they are easy to move. Imagine trying to run a 100-meter dash wearing track shoes that were as massive as bowling balls. It would be difficult to accelerate away from the starting blocks. Finally, think of the shot put. It takes muscle because the shot is massive, not because it is heavy. Imagine throwing the

shot in space where it would have no weight. It would still be massive, and it would take great effort to start it moving.

Mass is a unique measure of the amount of material in an object. Using the metric system (Appendix A), mass is measured in kilograms.



Mass is not the same as weight.

MASS | ENERGY | TEMPERATURE AND HEAT | DENSITY | PRESSURE

Table 5-1 | Newton's Three Laws of Motion

- I. A body continues at rest or in uniform motion in a straight line unless acted on by some force.
- II. The acceleration of a body is inversely proportional to its mass, directly proportional to the force, and in the same direction as the force.
- III. To every action, there is an equal and opposite reaction.

Newton's first law of motion is really a restatement of Galileo's law of inertia. An object continues at rest or in uniform motion in a straight line unless acted on by some force. Astronauts drifting in space will travel at constant rates in straight lines forever if no forces act on them (■ Figure 5-5a).

Newton's first law also explains why a projectile continues to move after all forces have been removed—for instance, how an arrow continues to move after leaving the bowstring. The object continues to move because it has momentum. You can think of an object's **momentum** as a measure of its amount of motion.

An object's momentum is equal to its velocity times its mass. A paper clip tossed across a room has low velocity and therefore little momentum, and you could easily catch it in your hand. But the same paper clip fired at the speed of a rifle bullet would have tremendous momentum, and you would not dare try to catch it. Momentum also depends on the mass of an object (**Focus on**

Fundamentals 1). Now imagine that, instead of tossing a paper clip, someone tosses you a bowling ball. A bowling ball contains much more mass than a paper clip and therefore has much greater momentum, even though it is moving at the same velocity.

Newton's second law of motion is about forces. Where Galileo spoke only of accelerations, Newton saw that an acceleration is the result of a force acting on a mass (Figure 5-5b). Newton's second law is commonly written as

$$F = ma$$

As always, you must define terms carefully when you look at an equation. An **acceleration** is a change in velocity, and a **velocity** is a directed speed. Most people use the words *speed* and *velocity* interchangeably, but they mean two different things. Speed is a rate of motion and does not have any direction associated with it, but velocity does. If you drive a car in a circle at 55 mph, your speed is constant, but your velocity is changing because your direction of motion is changing. An object experiences an acceleration if its speed changes or if its direction of motion changes. Every automobile has three accelerators—the gas pedal, the brake pedal, and the steering wheel. All three change the car's velocity.

In a way, the second law is just common sense; you experience its consequences every day. The acceleration of a body is proportional to the force applied to it. If you push gently against a grocery cart, you expect a small acceleration. The second law of motion also says that the acceleration depends on the mass of the body. If your grocery cart is filled with bricks and you push it gently, you expect

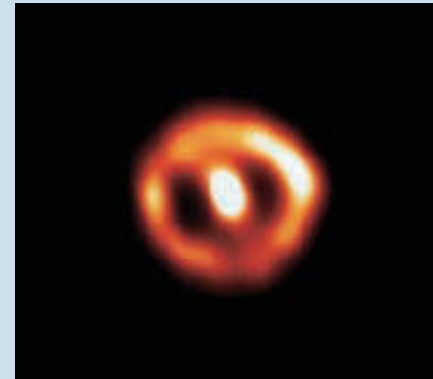
Cause and Effect

Why is the principle of cause and effect so important to scientists? One of the most often used and least often stated principles of science is cause and effect. Modern scientists all believe that events have causes, but ancient philosophers such as Aristotle argued that objects moved because of tendencies. They said that earth and water, and objects made mostly of earth and water, had a natural tendency to move toward the center of the universe. This natural motion had no cause but was inherent in the nature of the objects. Newton's second law of motion ($F = ma$) was the first clear statement of the principle of cause and effect. If an object (of mass m) changes its motion (a in the equation), then it must be acted on by a force (F in the equation). Any effect (a) must be the result of a cause (F).

The principle of cause and effect goes far beyond motion. It gives scientists confidence that every effect has a cause. The struggle

against disease is an example. Cholera is a horrible disease that can kill its victims in hours. Long ago it was probably blamed on bad magic or the will of the gods, and only two centuries ago it was blamed on "bad air." When an epidemic of cholera struck England in 1854, Dr. John Snow carefully mapped cases in London showing that the victims had drunk water from a small number of wells contaminated by sewage. In 1876, the German Dr. Robert Koch traced cholera to an even more specific cause when he identified the microscopic bacillus that causes the disease. Step by step, scientists tracked down the cause of cholera.

If the universe did not depend on cause and effect, then you could never expect to understand how nature works. Newton's second law of motion was arguably the first clear statement that the behavior of the universe depends rationally on causes.



Cause and effect: Why did this star explode in 1992? There must have been a cause. (ESA/STScI and NASA)

very little result. If it is full of inflated balloons, however, it will move easily in response to a gentle push. Finally, the second law says that the resulting acceleration is in the direction of the force. This is also what you would expect. If you push on a cart that is not moving, you expect it to begin moving in the direction you push.

The second law of motion is important because it establishes a precise relationship between cause and effect (**How Do We Know? 5-1**). Objects do not just move. They accelerate due to the action of a force. Moving objects do not just stop. They decelerate due to a force. And moving objects don't just change direction for no reason. Any change in direction is a change in

velocity and requires the presence of a force. Aristotle said that objects move because they have a tendency to move. Newton said that objects move due to a specific cause, a force.

Newton's third law of motion specifies that for every action there is an equal and opposite reaction. In other words, forces must occur in pairs directed in opposite directions. For example, if you stand on a skateboard and jump forward, the skateboard will shoot away backward. As you jump, your feet must exert a force against the skateboard, which accelerates it toward the rear. But forces must occur in pairs, so the skateboard must exert an equal but opposite force on your feet, and that is what accelerates your body forward (Figure 5-5c).

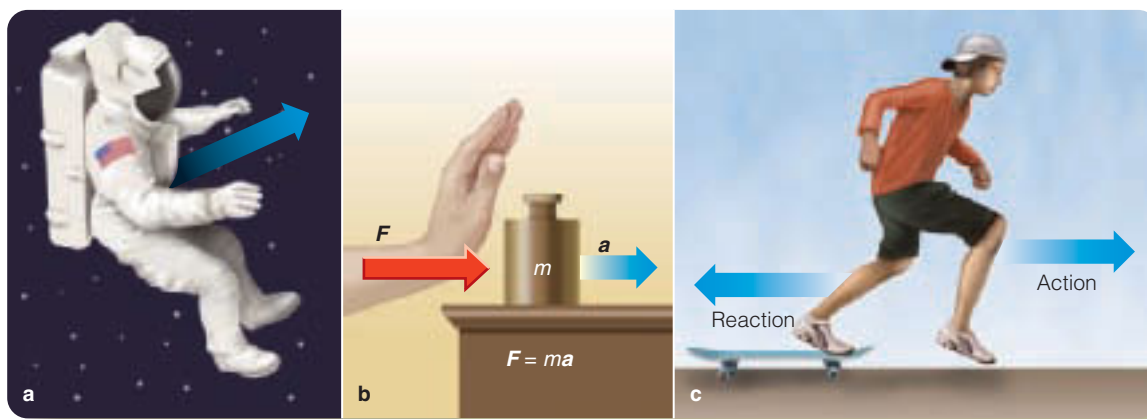


Figure 5-5

Newton's three laws of motion.

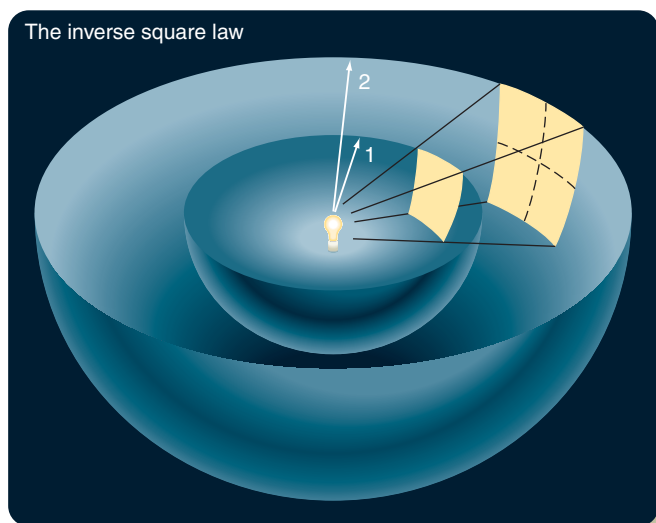
Mutual Gravitation

Once Newton understood the three laws of motion, he was able to consider the force that causes objects to fall. The first and second laws tell you that falling bodies accelerate downward because some force must be pulling downward on them. Newton realized that some force has to act on the moon. The moon follows a curved path around Earth, and motion along a curved path is accelerated motion. The second law of motion says that an acceleration requires a force, so a force must be making the moon follow that curved path.

Newton wondered if the force that holds the moon in its orbit could be the same force that causes apples to fall—gravity. He was aware that gravity extends at least as high as the tops of mountains, but he did not know if it could extend all the way to the moon. He believed that it could, but he thought it would be weaker at greater distances, and he guessed that its strength would decrease as the square of the distance increased.

This relationship, the **inverse square law**, was familiar to Newton from his work on optics, where it applied to the intensity of light. A screen set up 1 meter from a candle flame receives a certain amount of light on each square meter. However, if that screen is moved to a distance of 2 meters, the light that originally illuminated 1 square meter must now cover 4 square meters (■ Figure 5-6). Consequently, the intensity of the light is inversely proportional to the square of the distance to the screen.

Newton made a second assumption that enabled him to predict the strength of Earth's gravity at the distance of the moon. Not only did he assume that the strength of gravity follows the inverse square law, but he also assumed that the critical



■ **Figure 5-6**

As light radiates away from a source, it spreads out and becomes less intense. Here the light falling on one square meter on the inner sphere must cover four square meters on a sphere twice as big. This shows how the intensity of light is inversely proportional to the square of the distance.

distance is the distance from Earth's center, not the distance from Earth's surface. Because the moon is about 60 Earth radii away, Earth's gravity at the distance of the moon should be about 60^2 times less than at Earth's surface. Instead of being 9.8 m/s^2 at Earth's surface, it should be about 0.0027 m/s^2 at the distance of the moon.

Now, Newton wondered, was this enough acceleration to keep the moon in orbit? He knew the moon's distance and its orbital period, so he could calculate the actual acceleration needed to keep it in its curved path. The answer turned out to be 0.0027 m/s^2 , as his inverse-square-law calculations predicted. The moon is held in its orbit by gravity, and gravity obeys the inverse square law.

Newton's third law says that forces always occur in pairs, so if Earth pulls on the moon, then the moon must pull on Earth. This is called mutual gravitation and is a general property of the universe. The sun, the planets, and all their moons must also attract each other by mutual gravitation. In fact, every particle of mass in the universe must attract every other particle, which is why Newtonian gravity is often called universal mutual gravitation.

Clearly the force of gravity depends on mass. Your body is made of matter, and you have your own personal gravitational field. But your gravity is weak and does not attract personal satellites orbiting around you. Larger masses have stronger gravity. From an analysis of the third law of motion, Newton realized that the mass that resists acceleration in the first law is identical to the mass associated with causing gravity. Newton performed precise experiments with pendulums and confirmed this equivalence between the mass that resists acceleration and the mass that produces gravity.

From this, combined with the inverse square law, he was able to write the famous formula for the gravitational force between two masses, M and m :

$$F = -\frac{GMm}{r^2}$$

The constant G is the gravitational constant; it is the constant that connects mass to gravity. In the equation, r is the distance between the masses. The negative sign means that the force is attractive, pulling the masses together and making r decrease. In plain English, Newton's law of gravitation says: The force of gravity between two masses M and m is proportional to the product of the masses and inversely proportional to the square of the distance between them.

Newton's description of gravity was a difficult idea for physicists of his time to accept because it is an example of action at a distance. Earth and moon exert forces on each other even though there is no physical connection between them. Modern scientists resolve this problem by referring to gravity as a **field**. Earth's presence produces a gravitational field directed toward Earth's center. The strength of the field decreases according to the inverse square law. Any particle of mass in that field experiences a force that depends on the mass of the particle and the strength of the field

at the particle's location. The resulting force is directed toward the center of the field.

The field is an elegant way to describe gravity, but it still does not say what gravity is. Later in this chapter, when you learn about Einstein's theory of curved space-time, you will get a better idea of what gravity really is.

SCIENTIFIC ARGUMENT

What do the words universal and mutual mean when you say "universal mutual gravitation"?

Scientists often build arguments that proceed step by step, and this is a good example. Newton argued that the force that makes an apple accelerate downward is the same as the force that accelerates the moon and holds it in its orbit. The third law of motion says that forces always occur in pairs, so if Earth attracts the moon, then the moon must attract Earth. That is, gravitation is *mutual* between any two objects.

Furthermore, if Earth's gravity attracts the apple and the moon, then it must attract the sun, and the third law says that the sun must attract Earth. But if the sun attracts Earth, then it must also attract the other planets and even distant stars, which, in turn, must attract the sun and each other. Step by step, Newton's third law of motion leads to the conclusion that gravitation must apply to all masses in the universe. That is, gravitation must be *universal*.

Aristotle explained gravity in a totally different way. **Why couldn't Aristotle's explanation of a falling apple on Earth account for a hammer falling on the surface of the moon?**

5-2 Orbital Motion and Tides

ORBITAL MOTION AND TIDES are two different kinds of gravitational phenomena. As you think about the orbital motion of the moon and planets, you need to think about how gravity pulls on an object. When you think about tides, you must think about how gravity pulls on different parts of an object. Analyzing these two kinds of phenomena will give you a deeper insight into how gravity works.

Orbits

Newton was the first person to realize that objects in orbit are falling. You can explore Newton's insight by analyzing the motion of objects orbiting Earth. Carefully read **Orbiting Earth** on pages 84–85 and notice three important concepts and six new terms.

1 An object orbiting Earth is actually falling (being accelerated) toward Earth's center. The object continuously misses Earth because of its orbital velocity. To follow a circular orbit, the object must move at *circular velocity*, and at the

right distance from Earth it could be a very useful *geosynchronous satellite*.

2 Notice that objects orbiting each other actually revolve around their *center of mass*.

3 Finally, notice the difference between *closed orbits* and *open orbits*. If you want to leave Earth never to return, you must accelerate your spaceship at least to *escape velocity*, V_e , so it will follow an open orbit.

Orbital Velocity

If you were about to ride a rocket into orbit, you would have to answer a critical question: "How fast must I go to stay in orbit?" An object's circular velocity is the lateral velocity it must have to remain in a circular orbit. If you assume that the mass of your spaceship is small compared with the mass of Earth, then the circular velocity is:

$$V_c = \sqrt{\frac{GM}{r}}$$

In this formula, M is the mass of the central body (Earth in this case) in kilograms, r is the radius of the orbit in meters, and G is the gravitational constant, $6.67 \times 10^{-11} \text{ m}^3/\text{s}^2\text{kg}$. This formula is all you need to calculate how fast an object must travel to stay in a circular orbit.

For example, how fast does the moon travel in its orbit? Earth's mass is $5.97 \times 10^{24} \text{ kg}$, and the radius of the moon's orbit is $3.84 \times 10^8 \text{ m}$. Then the moon's velocity is:

$$\begin{aligned} V_c &= \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{3.84 \times 10^8}} = \sqrt{\frac{39.9 \times 10^{13}}{3.84 \times 10^8}} \\ &= \sqrt{1.04 \times 10^6} = 1020 \text{ m/s} = 1.02 \text{ km/s} \end{aligned}$$

This calculation shows that the moon travels 1.02 km along its orbit each second. That is the circular velocity at the distance of the moon.

A satellite just above Earth's atmosphere is only about 200 km above Earth's surface, or 6578 km from Earth's center, so Earth's gravity is much stronger, and the satellite must travel much faster to stay in a circular orbit. You can use the formula above to find that the circular velocity just above Earth's atmosphere is about 7780 m/s, or 7.7 km/s. This is about 17,400 miles per hour, which shows why putting satellites into Earth orbit takes such large rockets. Not only must the rocket lift the satellite above Earth's atmosphere, but the rocket's trajectory must then curve over and accelerate the satellite horizontally to circular velocity.

A **Common Misconception** holds that there is no gravity in space. You can see that space is filled with gravitational forces from Earth, the sun, and all other objects in the universe. An astronaut who appears weightless in space is actually falling along a path at the urging of the combined gravitational fields in the rest of the universe. Just above Earth's atmosphere, the orbital motion of the astronaut is dominated by Earth's gravity.

Calculating Escape Velocity

If you launch a rocket upward, it will consume its fuel in a few moments and reach its maximum speed. From that point on, it will coast upward. How fast must a rocket travel to coast away from Earth and escape? Of course, no matter how far it travels, it can never escape from Earth's gravity. The effects of Earth's gravity extend to infinity. It is possible, however, for a rocket to travel so fast initially that gravity can never slow it to a stop. Then the rocket could leave Earth.

Escape velocity is the velocity required to escape from the surface of an astronomical body. Here you are interested in escaping from Earth or a planet; in later chapters you will consider the escape velocity from stars, galaxies, and even black holes.

The escape velocity, V_c , is given by a simple formula:

$$V_c = \sqrt{\frac{2GM}{r}}$$

Again, G is the gravitational constant $6.67 \times 10^{-11} \text{ m}^3/\text{s}^2\text{kg}$, M is the mass of the astronomical body in kilograms, and r is its radius in meters. (Notice that this formula is very similar to the formula for circular velocity; in fact the escape velocity formula is $\sqrt{2}$ times the circular velocity formula.)

You can find the escape velocity from Earth by again using its mass, $5.97 \times 10^{24} \text{ kg}$, and plugging in its radius, $6.38 \times 10^6 \text{ m}$. Then the escape velocity is:

$$\begin{aligned} V_c &= \sqrt{\frac{2 \times 6.67 \times 10^{-11} \times 5.97 \times 10^{24}}{6.38 \times 10^6}} = \sqrt{\frac{7.96 \times 10^{14}}{6.38 \times 10^6}} \\ &= \sqrt{1.25 \times 10^8} = 11,200 \text{ m/s} = 11.2 \text{ km/s} \end{aligned}$$

This is equal to about 24,600 miles per hour.

Notice from the formula that the escape velocity from a body depends on both its mass and radius. A massive body might have a low escape velocity if it has a very large radius. You will meet such objects when you consider giant stars. On the other hand, a rather low-mass body could have a very large escape velocity if it had a very small radius, a condition you will meet when you study black holes.

Once Newton understood gravity and motion, he could do what Kepler had failed to do—he could explain why the planets obey Kepler's laws of planetary motion.

Kepler's Laws Reexamined

Now that you understand Newton's laws, gravity, and orbital motion, you can look at Kepler's laws of planetary motion in a new and more sophisticated way.

Kepler's first law says that the orbits of the planets are ellipses with the sun at one focus. The orbits of the planets are ellipses because gravity follows the inverse square law. In one of his most famous mathematical proofs, Newton showed that if a planet moves in a closed orbit under the influence of an attractive force

that follows the inverse square law, then the planet must follow an elliptical path.

Even though Kepler correctly identified the shape of the planets' orbits, he still wondered why the planets keep moving along these orbits, and now you know the answer. They move because there is nothing to slow them down. Newton's first law says that a body in motion stays in motion unless acted on by some force. In the absence of friction, the planets must continue to move.

Kepler's second law says that a planet moves faster when it is near the sun and slower when it is farther away. Once again, Newton's discoveries explain why. Imagine you are in an elliptical orbit around the sun. After you round the most distant part of the ellipse, aphelion, you begin to move back closer to the sun, and the sun's gravity pulls you slightly forward in your orbit. You pick up speed as you fall closer to the sun, so, of course, you go faster as you approach the sun. After you round the closest point to the sun, perihelion, you begin to move away from the sun, and the sun's gravity pulls slightly backward on you, slowing you down as you climb away from the sun. If you were in a circular orbit, the sun's gravity would always pull perpendicular to your motion, and you would not speed up or slow down. So Kepler's second law makes sense when you analyze it in terms of forces and motions.

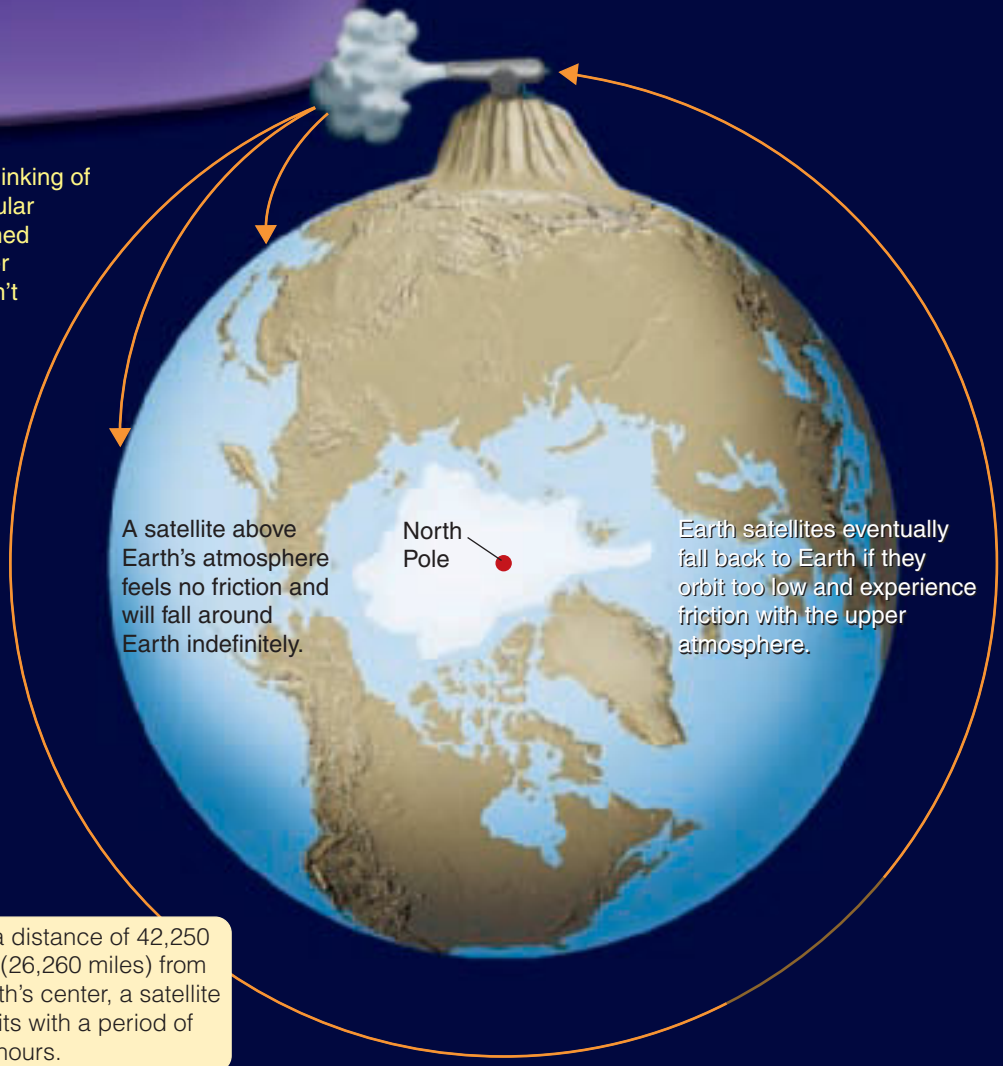
Physicists think of Kepler's second law in a more elegant way. Earlier you saw that a body moving on a frictionless surface will continue to move in a straight line until it is acted on by some force; that is, the object has momentum. In a similar way, an object set rotating on a frictionless surface will continue rotating until something acts to speed it up or slow it down. Such an object has **angular momentum**, a measure of the rotation of the body about some point. A planet circling the sun in an orbit has a given amount of angular momentum; and, with no outside influences to alter its motion, it must conserve its angular momentum. That is, its angular momentum must remain constant. Mathematically, a planet's angular momentum is the product of its mass, velocity, and distance from the sun. This explains why a planet must speed up as it comes closer to the sun along an elliptical orbit. Because its angular momentum is conserved, as its distance from the sun decreases, its velocity must increase. Conversely, the planet's velocity must decrease as its distance from the sun increases.

The conservation of angular momentum is actually a common human experience. Skaters spinning slowly can draw their arms and legs closer to their axis of rotation and, through conservation of angular momentum, spin faster (■ Figure 5-7). To slow their rotation, they can extend their arms again. Similarly, divers can spin rapidly in the tuck position and then slow their rotation by stretching into the extended position.

Kepler's third law says that a planet's orbital period depends on its distance from the sun. That law is also explained by a conservation law, but in this case it is the law of conservation of

Orbiting Earth

1 You can understand orbital motion by thinking of a cannonball falling around Earth in a circular path. Imagine a cannon on a high mountain aimed horizontally as shown at right. A little gunpowder gives the cannonball a low velocity, and it doesn't travel very far before falling to Earth. More gunpowder gives the cannonball a higher velocity, and it travels farther. With enough gunpowder, the cannonball travels so fast it never strikes the ground. Earth's gravity pulls it toward Earth's center, but Earth's surface curves away from it at the same rate it falls. It is in orbit. The velocity needed to stay in a circular orbit is called the **circular velocity**. Just above Earth's atmosphere, circular velocity is 7780 m/s or about 17,400 miles per hour, and the orbital period is about 90 minutes.



1a A **geosynchronous satellite** orbits eastward with the rotation of Earth and remains above a fixed spot — ideal for communications and weather satellites.

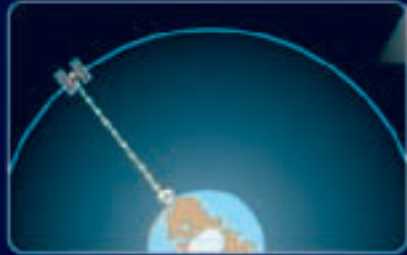
A Geosynchronous Satellite



At a distance of 42,250 km (26,260 miles) from Earth's center, a satellite orbits with a period of 24 hours.

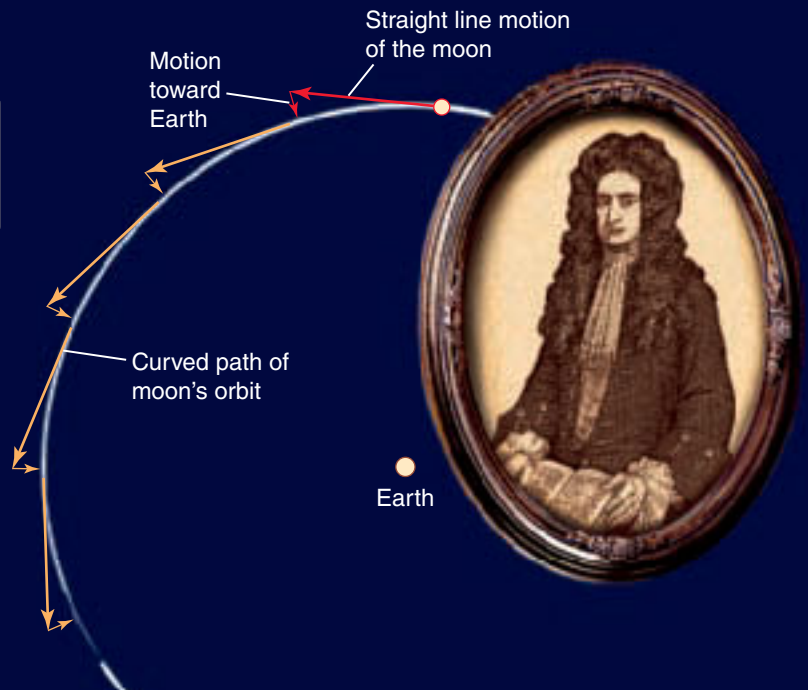


The satellite orbits eastward, and Earth rotates eastward under the moving satellite.

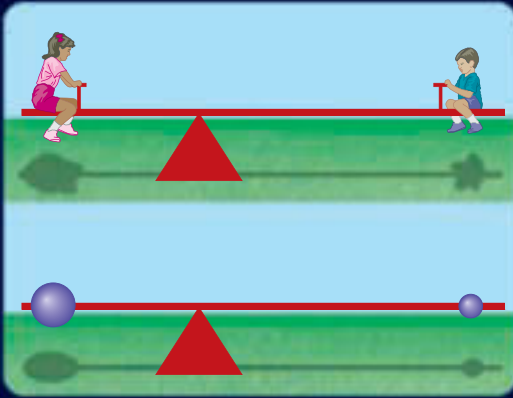


The satellite remains fixed above a spot on Earth's equator.

1b According to Newton's first law of motion, the moon should follow a straight line and leave Earth forever. Because it follows a curve, Newton knew that some force must continuously accelerate it toward Earth — gravity. Each second the moon moves 1020 m (3350 ft) eastward and falls about 1.6 mm (about 1/16 inch) toward Earth. The combination of these motions produces the moon's curved orbit. The moon is falling.

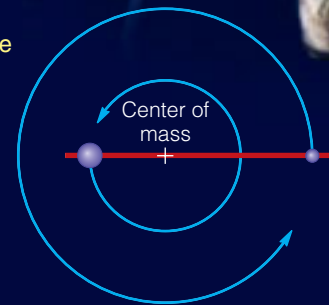


1c Astronauts in orbit around Earth feel weightless, but they are not “beyond Earth’s gravity,” to use a term from old science fiction movies. Like the moon, the astronauts are accelerated toward Earth by Earth’s gravity, but they travel fast enough along their orbits that they continually “miss the Earth.” They are literally falling around Earth. Inside or outside a spacecraft, astronauts feel weightless because they and their spacecraft are falling at the same rate. Rather than saying they are weightless, you should more accurately say they are in free fall.



2 To be precise you should not say that an object orbits Earth. Rather the two objects orbit each other. Gravitation is mutual, and if Earth pulls on the moon, the moon pulls on Earth. The two bodies revolve around their common **center of mass**, the balance point of the system.

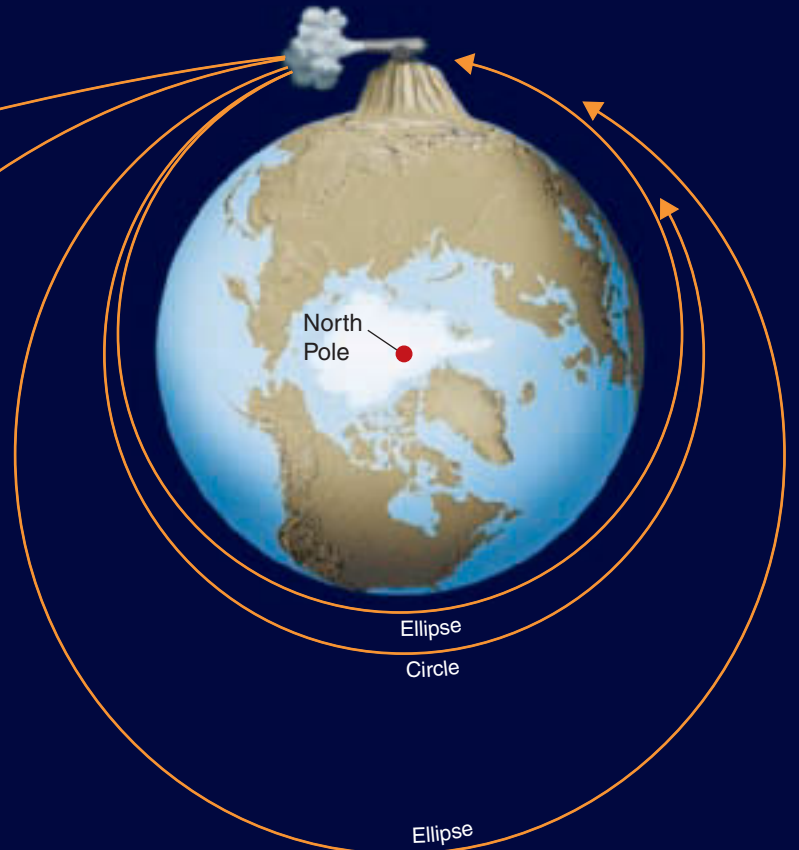
2a Two bodies of different mass balance at the center of mass, which is located closer to the more massive object. As the two objects orbit each other, they revolve around their common center of mass as shown at right. The center of mass of the Earth–moon system lies only 4708 km (2926 miles) from the center of Earth — inside the Earth. As the moon orbits the center of mass on one side, the Earth swings around the center of mass on the opposite side.



3 **Closed orbits** return the orbiting object to its starting point. The moon and artificial satellites orbit Earth in closed orbits. Below, the cannonball could follow an elliptical or a circular closed orbit. If the cannonball travels as fast as **escape velocity**, the velocity needed to leave a body, it will enter an open orbit. An **open orbit** does not return the cannonball to Earth. It will escape.

A cannonball with a velocity greater than escape velocity will follow a hyperbola and escape from Earth.

A cannonball with escape velocity will follow a parabola and escape.



3a As described by Kepler’s second law, an object in an elliptical orbit has its lowest velocity when it is farthest from Earth (apogee), and its highest velocity when it is closest to Earth (perigee). Perigee must be above Earth’s atmosphere, or friction will rob the satellite of energy and it will eventually fall back to Earth.

Energy

Physicists define **energy** as the ability to do work, but you might paraphrase that definition as the ability to produce a change. A moving body has energy called **kinetic energy**. A planet moving along its orbit, a cement truck rolling down the highway, and a golf ball sailing down the fairway all have the ability to produce a change. Imagine colliding with any of these objects!

Energy need not be represented by motion. Sunlight falling on a green plant, on photographic film, or on unprotected skin can produce chemical changes, and thus light is a form of energy. Batteries and gasoline are examples of chemical energy, and uranium fuel rods contain nuclear energy. A tank of hot water contains thermal energy.

Potential energy is the energy an object has because of its position in a gravitational field. A bowling ball on a shelf above your desk has potential energy. It is only potential,

however, and doesn't produce any changes until the bowling ball descends onto your desk. The higher the shelf, the more potential energy the ball has.

Energy constantly flows through nature and produces changes. Sunlight (energy) is absorbed by ocean plants and stored as sugars and starches (energy). When the plant dies, it and other ocean life are buried and become oil (energy), which gets pumped to the surface and burned in automobile engines to produce motion (energy).

Aristotle believed that all change originated in the motion of the starry sphere and flowed down to Earth. Modern science has found a more sophisticated description of the continual change you see around you. In a way, science is the study of the way energy flows through the world and produces change. Energy is the pulse of the natural world.

Using the metric system (Appendix A), energy is expressed in **joules** (abbreviated **J**).

One joule is about as much energy as that given up when an apple falls from a table to the floor.



Energy is the ability to cause change.

MASS | ENERGY | TEMPERATURE AND HEAT | DENSITY | PRESSURE

energy (**Focus on Fundamentals 2**). A planet orbiting the sun has a specific amount of energy that depends only on its average distance from the sun. That energy can be divided between energy of motion and energy stored in the gravitational attraction between the planet and the sun. The energy of motion



■ **Figure 5-7**

Skaters demonstrate conservation of angular momentum when they spin faster by drawing their arms and legs closer to their axis of rotation.

depends on how fast the planet moves, and the stored energy depends on the size of its orbit. The relation between these two kinds of energy is determined by Newton's laws. That means there has to be a fixed relationship between the rate at which a planet moves around its orbit and the size of the orbit—between its orbital period P and the orbit's semimajor axis a . You can even derive Kepler's third law from Newton's laws of motion as shown in the next section.

Newton's Version of Kepler's Third Law

The equation for circular velocity is actually a version of Kepler's third law, as you can prove with three lines of simple algebra. The result is one of the most useful formulas in astronomy.

The equation for circular velocity, as you have seen, is:

$$V_c = \sqrt{\frac{GM}{r}}$$

The orbital velocity of a planet is simply the circumference of its orbit divided by the orbital period:

$$V = \frac{2\pi r}{P}$$

If you substitute this for V in the first equation and solve for P^2 , you will get:

$$P^2 = \frac{(4\pi^2)}{(GM)} r^3$$

Here M is just the total mass of the system in kilograms. For a planet orbiting the sun, you can use the mass of the sun for M , because the mass of the planet is negligible compared to the mass of the sun. (In a later chapter, you will apply this formula to two stars orbiting each other, and then the mass M will be the sum of the two masses.) For a circular orbit, r equals the semimajor axis a , so this formula is a general version of Kepler's third law, $P^2 = a^3$. In Kepler's version, you used astronomical units (AU) and years, but in Newton's version of the formula, you should use units of meters, seconds, and kilograms. G , of course, is the gravitational constant.

This is a powerful formula. Astronomers use it to calculate the masses of bodies by observing orbital motion. If, for example, you observed a moon orbiting a planet and you could measure the size of the moon's orbit, r , and its orbital period, P , you could use this formula to solve for M , the total mass of the planet plus the moon. There is no other way to find masses of objects in the universe, and, in later chapters, you will see this formula used over and over to find the masses of stars, galaxies, and planets.

This discussion is a good illustration of the power of Newton's work. By carefully defining motion and gravity and by giving them mathematical expression, Newton was able to derive new truths, among them Newton's version of Kepler's third law. His work transformed the mysterious wanderings of the planets into understandable motions that follow simple rules. In fact, his discovery of gravity explained something else that had mystified philosophers for millennia—the ebb and flow of the oceans.

Tides and Tidal Forces

Newton understood that gravity is mutual—Earth attracts the moon, and the moon attracts Earth—and that means the moon's gravity can explain the ocean tides.

Tides are caused by small differences in gravitational forces. For example, Earth's gravity attracts your body downward with a force equal to your weight. The moon is less massive and more distant, so it attracts your body with a force that is a tiny percent of your weight. You don't notice that little force, but Earth's oceans respond dramatically.

The side of Earth that faces the moon is about 4000 miles closer to the moon than is the center of Earth. Consequently, the moon's gravity, tiny though it is at the distance of Earth, is just a bit stronger when it acts on the near side of Earth than on the center. It pulls on the oceans on the near side of Earth a bit more strongly than on Earth's center, and the oceans respond by flowing into a bulge of water on the side of Earth facing the moon. There is also a bulge on the side of Earth that faces away from the moon because the moon pulls more strongly on Earth's center than on the far side. Thus the moon pulls Earth away from the oceans, which flow into a bulge away from the moon as shown at the top of ■ Figure 5-8.

You might wonder: If Earth and moon accelerate toward each other, why don't they smash together? The answer is that

they would collide in about two weeks except that they are orbiting around their common center of mass. The ocean tides are caused by the accelerations Earth and its oceans feel as they orbit around that center of mass.

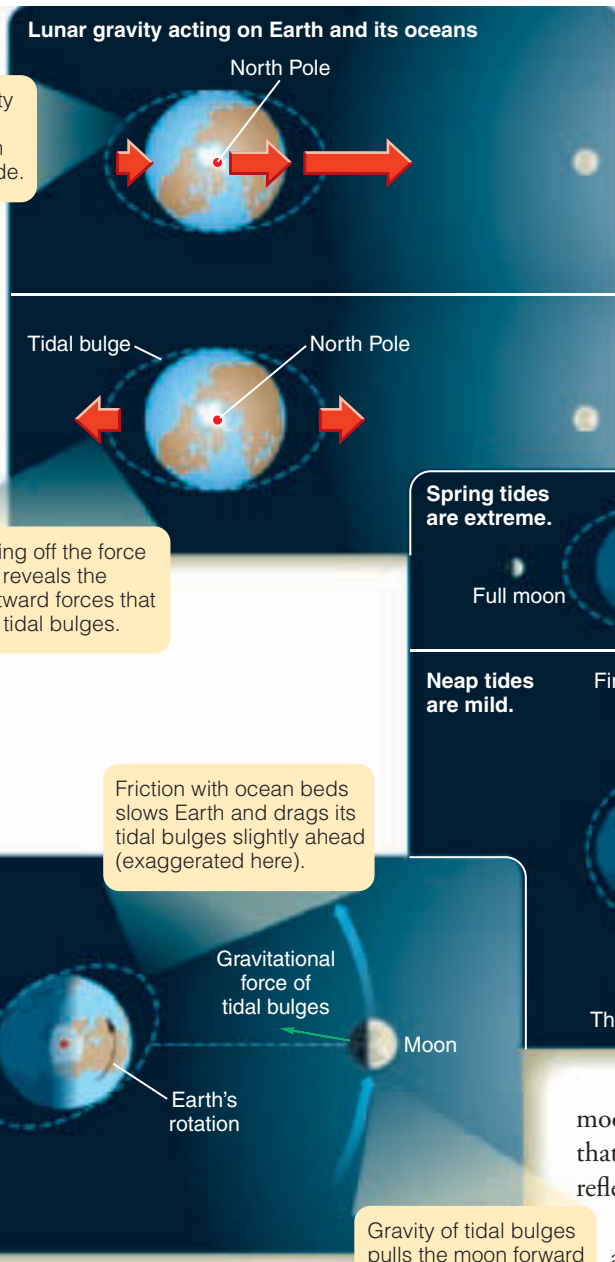
A **Common Misconception** holds that the moon's effect on tides means that the moon has an affinity for water—including the water in your body—and, according to some people, that's how the moon affects you. That's not true. If the moon's gravity affected only water, then there would be only one tidal bulge, the one facing the moon. As you know, the moon's gravity acts on the rock of Earth as well as on water, and that produces the tidal bulge in the oceans on the far side of Earth. In fact, small tidal bulges occur in the rocky bulk of Earth as it is deformed by the moon's gravity, and although you don't notice it, as Earth rotates, its mountains and plains rise and fall by a few centimeters. The moon has no special affinity for water, and, because your body is so much smaller than Earth, any tides the moon raises in your body are immeasurably small. Ocean tides are large because oceans are large.

You can see dramatic evidence of tides if you watch the ocean shore for a few hours. As Earth rotates on its axis, the tidal bulges remain fixed with respect to the moon. As the turning Earth carries you and your beach into a tidal bulge, the ocean water deepens, and the tide crawls up the sand. The tide does not so much “come in” as you are carried into the tidal bulge. Later, when Earth's rotation carries you out of the bulge, the ocean becomes shallower, and the tide falls. Because there are two bulges on opposite sides of Earth, the tides rise and fall twice a day on an ideal coast.

In reality, the tidal cycle at any given location can be quite complex because it is affected by the latitude of the site, shape of the shore, winds, and so on. Tides in the Bay of Fundy (New Brunswick, Canada), for example, occur twice a day and can exceed 40 feet. In contrast, the northern coast of the Gulf of Mexico has only one tidal cycle a day of roughly 1 foot.

Gravity is universal, so the sun also produces tides on Earth. The sun is roughly 27 million times more massive than the moon, but it lies almost 400 times farther from Earth. Tides on Earth caused by the sun are less than half as high as those caused by the moon. Twice a month, at new moon and at full moon, the moon and sun produce tidal bulges that add together and produce extreme tidal changes; high tide is exceptionally high, and low tide is exceptionally low. Such tides are called **spring tides**. Here the word *spring* does not refer to the season of the year but to the rapid welling up of water. At first- and third-quarter moons, the sun and moon pull at right angles to each other, and the sun's tides cancel out some of the moon's tides. These less-extreme tides are called **neap tides**, and they do not rise very high or fall very low. The word *neap* comes from an obscure Old English word, *nep*, that seems to have meant “lacking power to advance.” Spring tides and neap tides are illustrated in Figure 5-8.

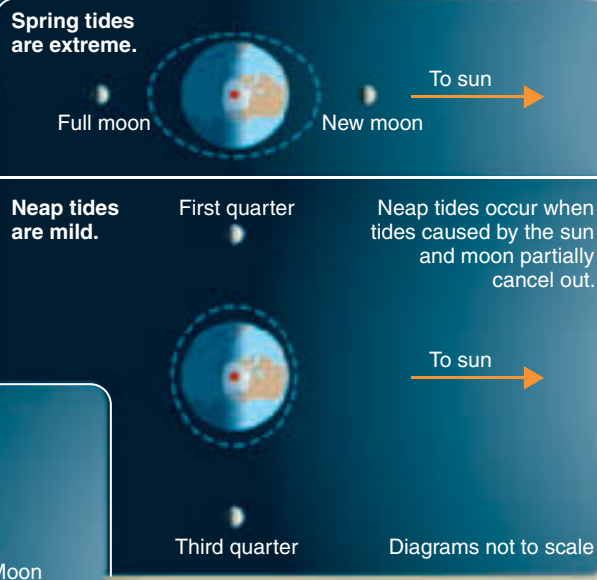
Galileo tried to understand tides, but it was not until Newton described gravity that astronomers could analyze tidal



■ **Figure 5-8**

Tides are produced by small differences in the gravitational force exerted on different parts of an object. The side of Earth nearest the moon feels a larger force than the side farthest away. Relative to Earth's center, small forces are left over, and they cause the tides. Both the moon and sun produce tides on Earth. Tides can alter both an object's rotation and its orbital motion.

Spring tides occur when tides caused by the sun and moon add together.



forces and recognize their surprising effects. For example, the moving water in tidal bulges experiences friction with the ocean beds and resistance as it runs into continents, and that slows Earth's rotation and makes the length of a day grow by 0.0023 second per century. Thin layers of silt laid down millions of years ago where rivers empty into the oceans record tidal cycles as well as daily, monthly, and annual cycles. Those confirm that only 620 million years ago Earth's day was less than 22 hours long. Tidal forces can also affect orbital motion. Earth rotates eastward, and friction with the ocean beds drags the tidal bulges slightly eastward out of a direct Earth–moon line. These tidal bulges are massive, and their gravitational field pulls the moon forward in its orbit, as shown at the bottom of Figure 5-8. As a result, the

moon's orbit is growing larger by about 3.8 cm a year, an effect that astronomers can measure by bouncing laser beams off reflectors left on the lunar surface by the Apollo astronauts.

Earth's gravitation exerts tidal forces on the moon, and although there are no bodies of water on the moon, friction within the flexing rock has slowed the moon's rotation to the point that it now keeps the same face toward Earth.

Newton's gravitation is much more than just the force that makes apples fall. In later chapters, you will see how tides can pull gas away from stars, rip galaxies apart, and melt the interiors of small moons orbiting near massive planets. Tidal forces produce some of the most surprising and dramatic processes in the universe.

Astronomy After Newton

Newton published his work in 1687 in a book called *Philosophiæ Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), now known simply as *Principia* (pronounced *Prin-KIP-ee-uh*) (■ Figure 5-9). It is one of the most important books ever written. *Principia* changed astronomy, changed science, and changed the way people think about nature.

Testing a Hypothesis by Prediction

How are the predictions of a hypothesis useful in science? (Note the careful use of language here, to distinguish a tentative hypothesis from a theory that is well confirmed.) Scientific hypotheses face in two directions. They look back into the past and explain phenomena previously observed. For example, Newton's laws of motion and gravity explained observations of the movements of the planets made over many centuries. But hypotheses also look forward in that they make predictions about what you should find as you explore further. For example, Newton's laws allowed astronomers to calculate the orbits of comets, predict their return, and eventually understand their origin.

Scientific predictions are important in two ways. First, if a prediction of a hypothesis is confirmed, scientists gain confidence that the hypothesis is a true description of nature. But predictions are important for a second reason. They can point the way to unexplored avenues of knowledge.

Particle physics is a field in which predictions have played a key role in directing

research. In the early 1970s, physicists proposed a hypothesis about the fundamental forces and particles in atoms called the Standard Model. This hypothesis explained what scientists had already observed in experiments, but it also predicted the existence of particles that hadn't yet been observed. To test the hypothesis, scientists focused their efforts on building more and more powerful particle accelerators in the hopes of detecting the predicted particles.

A number of these particles have since been discovered, and they do match the characteristics predicted by the Standard Model, further confirming the hypothesis. One predicted particle, the Higgs boson, has not yet been found, as of this writing, but an even larger accelerator may allow its detection. Will the Higgs boson be found, or will someone come up with a better hypothesis? This is only one of many cliff-hangers in modern science.

You learned in an earlier chapter that a hypothesis that has passed many tests and made successful predictions can "graduate" to



Physicists build huge accelerators to search for sub-atomic particles predicted by their theories. (Brookhaven National Laboratory)

being considered a theory. As you read about any scientific hypothesis or theory, think about both what it can explain and what it can predict.

Principia changed astronomy by ushering in a new age. No longer did people have to appeal to the whim of the gods to explain things in the heavens. No longer did they speculate on why the planets wander across the sky. After *Principia* astronomers understood that the motions of the heavenly bodies are governed by simple, universal rules that describe the motions of everything from orbiting planets to falling apples. Suddenly the universe was understandable in simple terms, and astronomers could accurately predict future planetary motions (**How Do We Know? 5-2**).

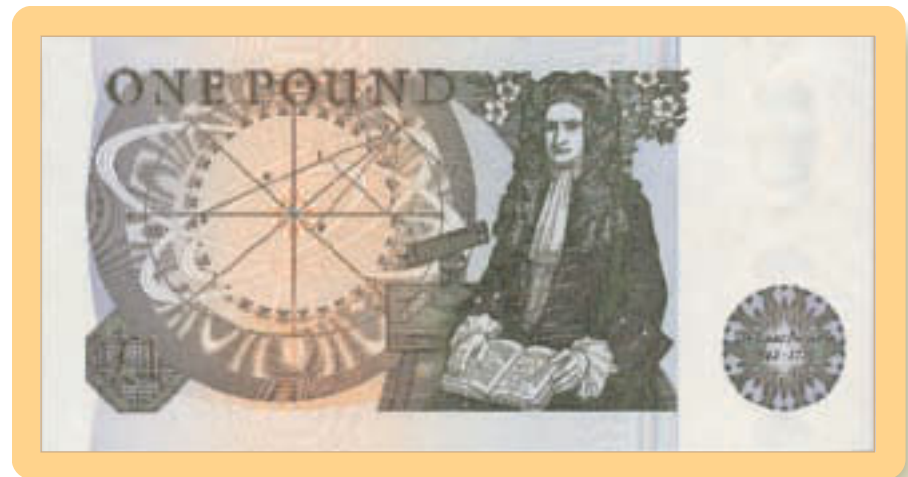
Principia also changed science in general. The works of Copernicus and Kepler had been mathematical, but no book before had so clearly demonstrated the power of mathematics as a language of precision. Newton's arguments in *Principia* were so powerful an illustration of the quantitative study of nature that scientists around the world adopted mathematics as their most powerful tool.

Also, *Principia* changed the way people thought about nature. Newton showed that the rules that govern the universe are simple.

Particles move according to three rules of motion and attract each other with a force called gravity. These motions are predictable, and that makes the universe a vast machine based on a few simple rules. It is complex only in that it contains a vast number

Figure 5-9

Newton, working from the discoveries of Galileo and Kepler, derived three laws of motion and the principle of mutual gravitation. He and some of his discoveries were honored on this old English pound note. Notice the diagram of orbital motion in the background and the open copy of *Principia* in Newton's hands.



of particles. In Newton's view, if he knew the location and motion of every particle in the universe, he could, in principle, derive the past and future of the universe in every detail. This mechanical determinism has been undermined by modern quantum mechanics, but it dominated science for more than two centuries during which scientists thought of nature as a beautiful clockwork that would be perfectly predictable if they knew how all the gears meshed.

Most of all, Newton's work broke the last bonds between science and formal philosophy. Newton did not speculate on the good or evil of gravity. He did not debate its meaning. Not more than a hundred years before, scientists would have argued over the "reality" of gravity. Newton didn't care for these debates. He wrote, "It is enough that gravity exists and suffices to explain the phenomena of the heavens."

Newton's laws dominated astronomy for two centuries. Then, early in the 20th century, Albert Einstein proposed a new way to describe gravity. The new theory did not replace Newton's laws but rather showed that they were only approximately correct and could be seriously in error under special circumstances. Einstein's theories further extend the scientific understanding of the nature of gravity. Just as Newton had stood on the shoulders of Galileo, Einstein stood on the shoulders of Newton.

SCIENTIFIC ARGUMENT

How do Newton's laws of motion explain the orbital motion of the moon?

The key here is to build your argument step by step. If Earth and the moon did not attract each other, the moon would move in a straight line in accord with Newton's first law of motion and vanish into deep space. Instead, gravity pulls the moon toward Earth's center, and the moon accelerates toward Earth. This acceleration is just enough to pull the moon away from its straight-line motion and cause it to follow a curve around Earth. In fact, it is correct to say that the moon is falling, but because of its lateral motion it continuously misses Earth.

Every orbiting object is falling toward the center of its orbit but is also moving laterally fast enough to compensate for the inward motion, and it follows a curved orbit. That is an elegant argument, but it raises a question: **How can astronauts float inside spacecraft in a "weightless" state? Why might "free fall" be a more accurate term?**

5-3 Einstein and Relativity

IN THE EARLY YEARS OF THE LAST CENTURY, Albert Einstein (1879–1955) (■ Figure 5-10) began thinking about how motion and gravity interact. He soon gained international fame by showing that Newton's laws of motion and gravity were only partially correct. The revised theory became known as the theory of relativity. As you will see, there are really two theories of relativity.



■ Figure 5-10

Einstein has become a symbol of the brilliant scientist. His fame began when he was a young man and thought deeply about the nature of motion. That led him to revolutionary insights into the meaning of space and time and a new understanding of gravity.

Special Relativity

Einstein began by thinking about how moving observers see events around them. His analysis led him to the first postulate of relativity, also known as the principle of relativity:

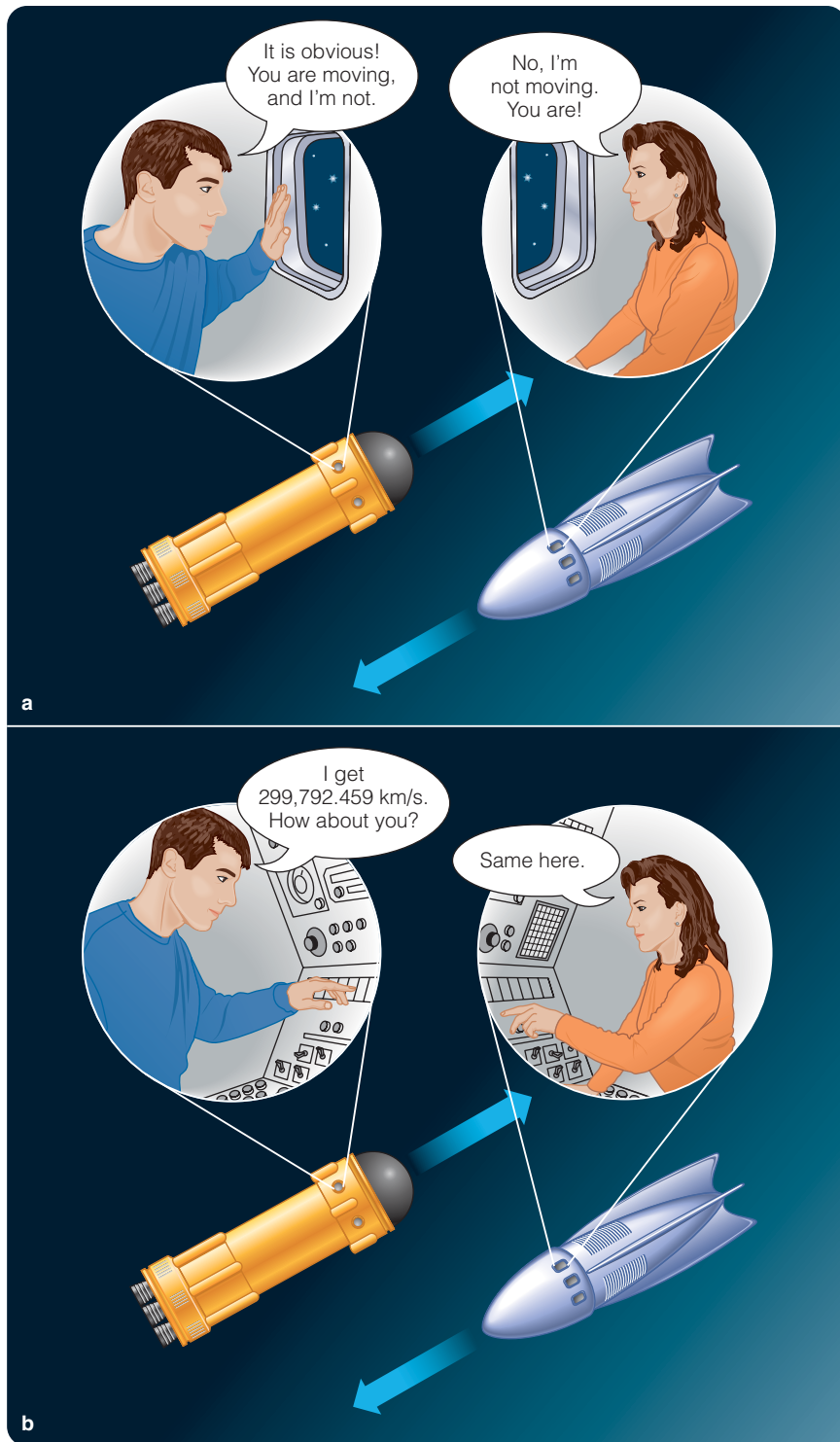
First postulate (the principle of relativity): Observers can never detect their *uniform* motion except relative to other objects.

You may have experienced the first postulate while sitting on a train in a station. You suddenly notice that the train on the next track has begun to creep out of the station. However, after several moments you realize that it is your own train that is moving and that the other train is still motionless on its track. You can't tell which train is moving until you look at external objects such as the station platform.

Consider another example. Suppose you are floating in a spaceship in interstellar space, and another spaceship comes coasting by (■ Figure 5-11a). You might conclude that it is moving and you are not, but someone in the other ship might be equally sure that you are moving and it is not. Of course, you could just look out a window and compare the motion of your spaceship with a nearby star, but that just expands the problem. Which is moving, your spaceship or the star? The principle of relativity says that there is no experiment you can perform to decide which ship is moving and which is not. This means that there is no such thing as absolute rest—all motion is relative.

Because neither you nor the people in the other spaceship could perform any experiment to detect your absolute motion through space, the laws of physics must have the same form in both spaceships. Otherwise, experiments would produce different results in the two ships, and you could decide who was moving. So, a more general way of stating the first postulate refers to these laws of physics:

First postulate (alternate version): The laws of physics are the same for all observers, no matter what their motion, so long as they are not *accelerated*.



■ **Figure 5-11**

(a) The principle of relativity says that observers can never detect their uniform motion, except relative to other objects. Thus, neither of these travelers can decide who is moving and who is not. (b) If the velocity of light depended on the motion of the observer through space, then these travelers could perform measurements inside their spaceships to discover who was moving. If the principle of relativity is correct, then the velocity of light must be a constant when measured by any observer.

The word *accelerated* is important. If either spaceship were to fire its rockets, then its velocity would change. The crew of that ship would know it because they would feel the acceleration pressing them into their couches. Accelerated motion, therefore, is different—the pilots of the spaceships can always tell which ship is accelerating and which is not. The postulates of relativity discussed here apply only to the special case of observers in *uniform* motion, which means *unaccelerated* motion. That is why the theory is called the **special theory of relativity**.

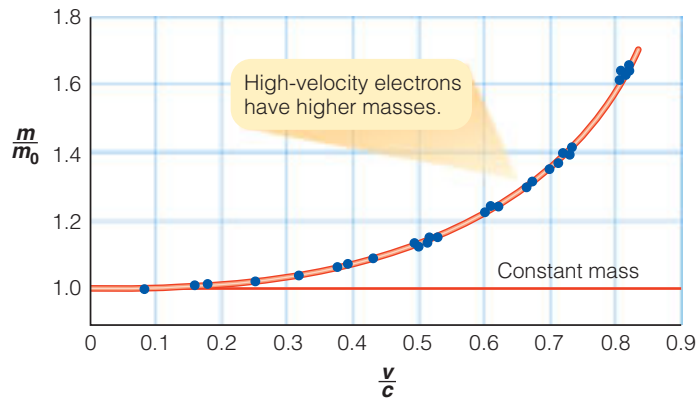
The first postulate led Einstein to the conclusion that the speed of light must be constant for all observers. No matter how you are moving, your measurement of the speed of light has to give the same result (Figure 5-11b). This became the second postulate of special relativity:

Second postulate: The speed of light is constant and will be the same for all observers independent of their motion relative to the light source.

Remember, this is required by the first postulate; if the speed of light were not constant, then the pilots of the spaceships could measure the speed of light inside their spaceships and decide who was moving.

Once Einstein had accepted the basic postulates of relativity, he was led to some startling discoveries. Newton's laws of motion and gravity worked well as long as distances were small and velocities were low. But when Einstein began to think about very large distances or very high velocities, he realized that Newton's laws were no longer adequate to describe what happens. Instead, the postulates led Einstein to derive a more accurate description of nature now known as the special theory of relativity. It predicts some peculiar effects. For example, special relativity shows that the observed mass of a moving particle depends on its velocity. The higher the velocity, the greater the mass of the particle. This is not significant at low velocities, but it becomes very important as the velocity approaches the speed of light. Such increases in mass are actually observed whenever physicists accelerate atomic particles to high velocities (■ Figure 5-12).

This discovery led to yet another insight. The relativistic equations that describe the energy of a moving particle predict



■ **Figure 5-12**

The observed mass of moving electrons depends on their velocity. As the ratio of their velocity to the velocity of light, v/c , gets larger, the mass of the electrons in terms of their mass at rest, m/m_0 , increases. Such relativistic effects are quite evident in particle accelerators, which accelerate atomic particles to very high velocities.

that the energy of a motionless particle is not zero. Rather, its energy at rest is m_0c^2 . This is of course the famous equation:

$$E = m_0c^2$$

The constant c is the speed of light, and m_0 is the mass of the particle when it is at rest. This simple formula shows that mass and energy are related, and you will see in later chapters how nature can convert one into the other inside stars.

For example, suppose that you convert 1 kg of matter into energy. The speed of light is 3×10^8 m/s, so your result is 9×10^{16} joules (J) (approximately equal to a 20-megaton nuclear bomb). Recall that a joule is a unit of energy roughly equivalent to the energy given up when an apple falls from a table to the floor. This simple calculation shows that the energy equivalent of even a small mass is very large.

Other relativistic effects include the slowing of moving clocks and the shrinkage of lengths measured in the direction of motion. A detailed discussion of the major consequences of the special theory of relativity is beyond

the scope of this book, but you can have confidence that these strange effects have been confirmed many times in experiments. Einstein's work is called the special *theory* of relativity because it meets the scientific definition of a *theory*: it is very well understood, has been checked many times in many ways, and is widely applicable.

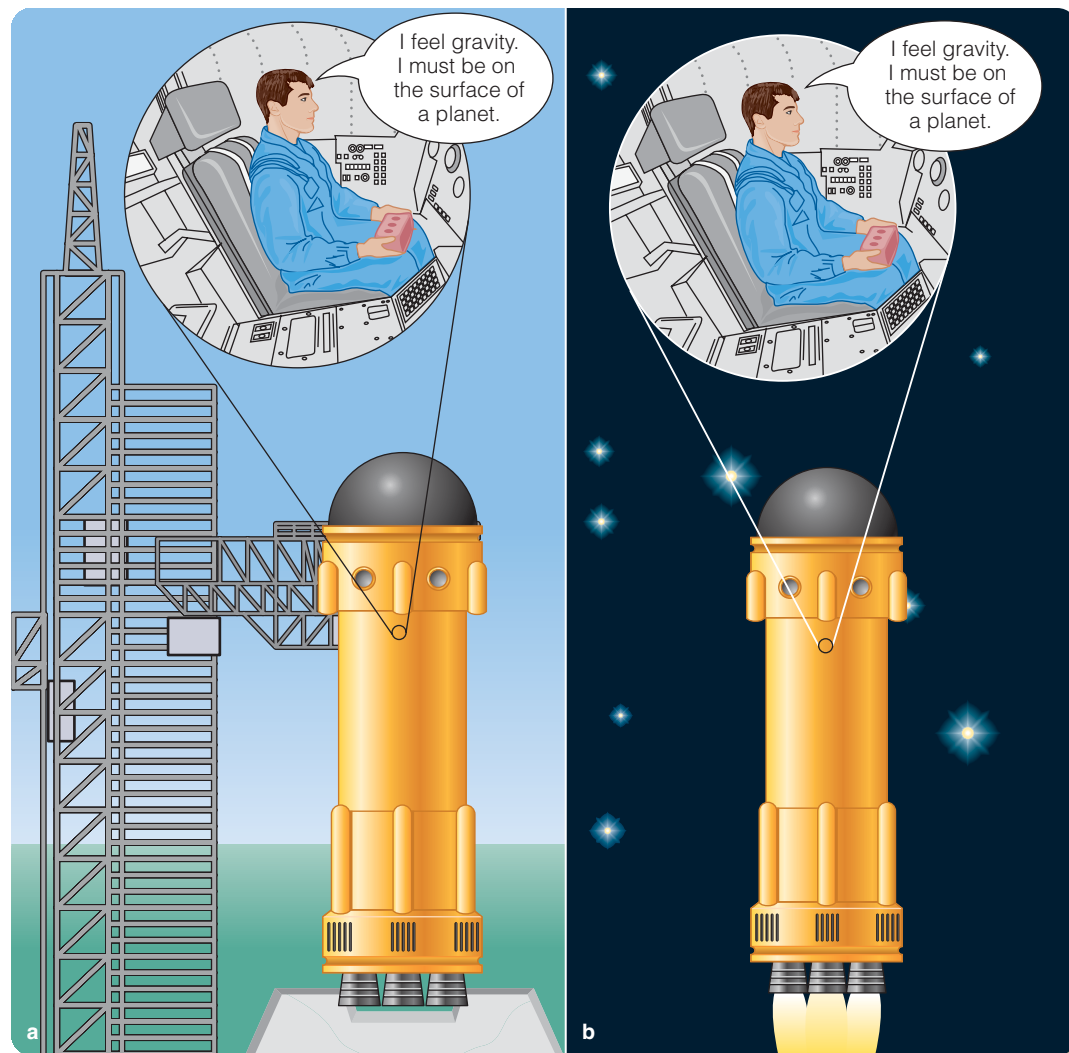
The General Theory of Relativity

In 1916, Einstein published a more general version of the theory of relativity that dealt with accelerated as well as uniform motion. This **general theory of relativity** contained a new description of gravity.

Einstein began by thinking about observers in accelerated motion. Imagine an observer sitting in a windowless spaceship. Such an observer cannot distinguish between the force of gravity and the inertial forces produced by the acceleration of the spaceship (■ Figure 5-13). This led Einstein to conclude that gravity

■ **Figure 5-13**

(a) An observer in a closed spaceship on the surface of a planet feels gravity. (b) In space, with the rockets smoothly firing and accelerating the spaceship, the observer feels inertial forces that are equivalent to gravitational forces.



and acceleration are related, a conclusion now known as the equivalence principle:

Equivalence principle: Observers cannot distinguish locally between inertial forces due to acceleration and uniform gravitational forces due to the presence of a massive body.

This should not surprise you. Earlier in this chapter you read that Newton concluded that the mass that resists acceleration is the same as the mass that exerts gravitational forces. He even performed an elegant experiment with pendulums to test the equivalence of the mass related to motion and the mass related to gravity.

The importance of the general theory of relativity lies in its description of gravity. Einstein concluded that gravity, inertia, and acceleration are all associated with the way space is related to time in what is now referred to as space-time. This relation is often referred to as curvature, and a one-line description of general relativity explains a gravitational field as a curved region of space-time:

Gravity according to general relativity: Mass tells space-time how to curve, and the curvature of space-time (gravity) tells mass how to accelerate.

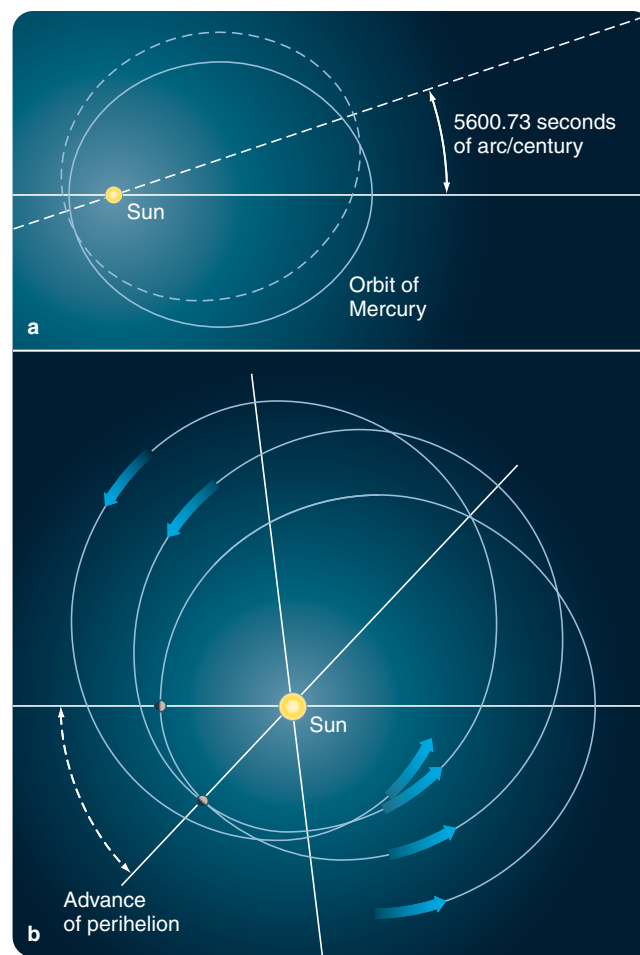
So, you feel gravity because Earth's mass causes a curvature of space-time. The mass of your body responds to that curvature by accelerating toward Earth's center, and that presses you downward in your chair. According to general relativity, all masses cause curvature, and the larger the mass, the more severe the curvature. That's gravity.

Confirmation of the Curvature of Space-Time

Einstein's general theory of relativity has been confirmed by a number of experiments, but two are worth mentioning here because they were among the first tests of the theory. One involves Mercury's orbit, and the other involves eclipses of the sun.

Johannes Kepler understood that the orbit of Mercury is elliptical, but it wasn't until 1859 that astronomers discovered that the long axis of its orbit sweeps around the sun in a motion that is an example of precession (■ Figure 5-14). The total observed precession is a little over 1.5° per century. This precession is produced by the gravitation of Venus, Earth, and the other planets and by the precession of Earth's axis. However, when astronomers take all known effects into account and use Newton's description of gravity to account for the gravitational influence of all of the planets, they are left with a small excess. Mercury's orbit is advancing 43 seconds of arc per century faster than Newton's laws predict.

This is a tiny effect. Each time Mercury returns to perihelion, its closest point to the sun, it is about 29 km (18 mi) past the position predicted by Newton's laws. This is such a small



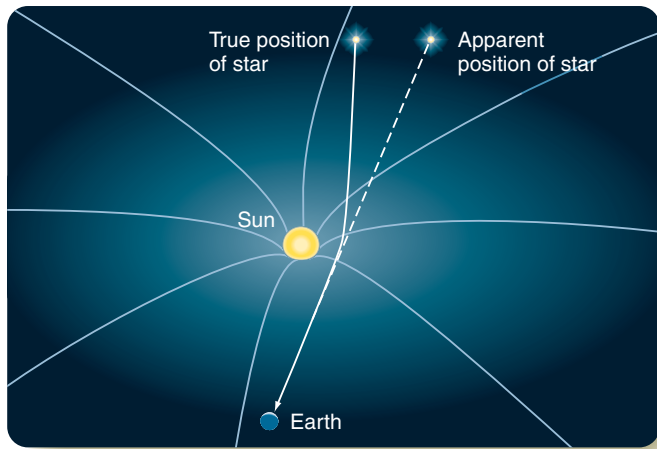
■ **Figure 5-14**

(a) Mercury's orbit precesses 43.11 arc seconds per century faster than predicted by Newton's laws. (b) Even when you ignore the influences of the other planets, Mercury's orbit is not a perfect ellipse. Curved space-time near the sun distorts the orbit from an ellipse into a rosette. The advance of Mercury's perihelion is exaggerated about a million times in this figure.

distance compared with the planet's diameter of 4850 km that it could never have been detected had it not been cumulative. Each orbit, Mercury gains 29 km, and in a century it gains over 12,000 km—more than twice its own diameter. This tiny effect, called the advance of perihelion of Mercury's orbit, accumulated into a serious discrepancy in the Newtonian description of the universe.

The advance of perihelion of Mercury's orbit was one of the first problems to which Einstein applied the principles of general relativity. First he calculated how much the sun's mass curves space-time in the region of Mercury's orbit, and then he calculated how Mercury moves through the space-time. The theory predicted that the curved space-time should cause Mercury's orbit to advance by 43.03 seconds of arc per century, well within the observational accuracy of the excess (Figure 5-14b).

When his theory matched observations, Einstein was so excited he could not return to work for three days. He would be



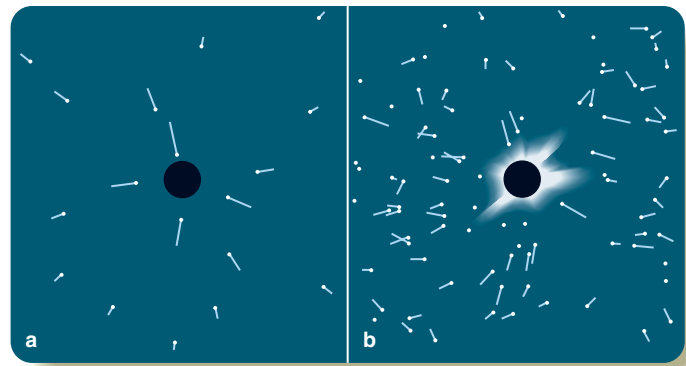
■ **Figure 5-15**

Like a depression in a putting green, the curved space-time near the sun deflects light from distant stars and makes them appear to lie slightly farther from the sun than their true positions.

even happier with modern studies that have shown that Mercury, Venus, Earth, and even Icarus, an asteroid that comes close to the sun, have orbits observed to be slipping forward due to the curvature of space-time near the sun. This same effect has been detected in pairs of stars that orbit each other.

A second test of general relativity was directly related to the motion of light through the curved space-time near the sun. Because light has a limited speed, Newton's laws predict that the gravity of an object should slightly bend the paths of light beams passing nearby. The equations of general relativity indicated that light would have an extra deflection caused by curved space-time, just as a rolling golf ball is deflected by undulations in a putting green. Einstein predicted that starlight grazing the sun's surface would be deflected by 1.75 arc seconds, twice the deflection that Newton's law of gravity would predict (■ Figure 5-15). Starlight passing near the sun is normally lost in the sun's glare, but during a total solar eclipse stars beyond the sun can be seen. As soon as Einstein published his theory, astronomers rushed to observe such stars and test the curvature of space-time.

The first solar eclipse following Einstein's announcement in 1916 occurred on June 8, 1918. It was cloudy at some observing sites, and results from other sites were inconclusive. The next occurred on May 29, 1919, only months after the end of World War I, and was visible from Africa and South America. British teams went to both Brazil and Príncipe, an island off the coast of



■ **Figure 5-16**

(a) Schematic drawing of the deflection of starlight by the sun's gravity. Dots show the true positions of the stars as photographed months before the eclipse. Lines point toward the positions of the stars during the eclipse. (b) Actual data from the eclipse of 1922. Random uncertainties of observation cause some scatter in the data, but in general the stars appear to move away from the sun by 1.77 arc seconds at the edge of the sun's disk. The deflection of stars is magnified by a factor of 2300 in both (a) and (b).

Africa. Months before the eclipse, they photographed the part of the sky where the sun would be located during the eclipse and measured the positions of the stars on the photographic plates. Then, during the eclipse, they photographed the same star field with the eclipsed sun located in the middle. After measuring the plates, they found slight changes in the positions of the stars. During the eclipse, the positions of the stars on the plates were shifted outward, away from the sun (■ Figure 5-16). If a star had been located at the edge of the solar disk, it would have been shifted outward by about 1.8 arc seconds. This represents good agreement with the theory's prediction.

Because the angles are so small, this is a very delicate observation, and it has been repeated at many total solar eclipses since 1919, with similar results. The most accurate results were obtained in 1973 when a Texas–Princeton team measured a deflection of 1.66 ± 0.18 arc seconds—good agreement with Einstein's theory.

The general theory of relativity is critically important in modern astronomy. You will meet the theory again in the discussions of black holes, distant galaxies, and the big bang universe. Einstein revolutionized modern physics by providing an explanation of gravity based on the geometry of curved space-time. Galileo's inertia and Newton's mutual gravitation are shown to be not just descriptive rules but fundamental properties of space and time.

SCIENTIFIC ARGUMENT

What does the equivalence principle tell you?

The equivalence principle says that there is no observation you can make inside a closed spaceship to distinguish between uniform acceleration and gravitation. Of course, you could open a window and look outside, but then you would no longer be in a closed spaceship. As long as you make no outside observations, you can't tell whether your spaceship is firing its rockets and accelerating through space or resting on the surface of a planet where gravity gives you weight.

Einstein took the equivalence principle to mean that gravity and acceleration through space-time are somehow related. The

general theory of relativity gives that relationship mathematical form and shows that gravity is really a distortion in space-time that physicists refer to as curvature. Consequently, you can say “mass tells space-time how to curve, and space-time tells mass how to accelerate.” The equivalence principle led Einstein to an explanation for gravity.

Einstein began his work by thinking carefully about common things such as what you feel when you are moving uniformly or accelerating. This led him to deep insights now called postulates. Special relativity sprang from two postulates. **Why does the second postulate have to be true if the first postulate is true?**

What Are We? Falling

Everything in the universe is falling. The moon is falling around Earth. Earth is falling along its orbit around the sun, and the sun and every other star in our galaxy are falling along their orbits around the center of our galaxy. Stars in other galaxies are falling around the center of those galaxies, and every galaxy in the universe is falling as it feels the gravitational tugs of every bit of matter that exists.

Newton's explanation of gravity as a force between two unconnected masses was action at a distance, and it offended many of the scientists of his time. They thought Newton's gravity seemed like magic. Einstein explained that gravity is a curvature of space-time and that every mass accelerates according to the curvature it feels around it. That's not action at a distance, and it can give you a new insight into how the universe works.

The mass of every atom in the universe contributes to the curvature, creating a universe filled with three-dimensional hills and valleys of curved space-time. You and your world, your sun, your galaxy, and every other object in the universe are falling through space guided by the curvature of space-time.

Study and Review

Summary

- ▶ Aristotle argued that the universe was composed of four elements: earth at the center, with water, air, and fire in layers above. **Natural motion (p. 77)** occurred when a displaced object returned to its natural place. **Violent motion (p. 77)** was motion other than natural motion and had to be sustained by a force.
- ▶ Galileo found that a falling object is accelerated; that is, it falls faster and faster with each passing second. The rate at which it accelerates, termed the **acceleration of gravity (p. 77)**, is 9.8 m/s^2 (32 ft/s^2) at Earth's surface and does not depend on the weight of the object, contrary to what Aristotle said.
- ▶ According to tradition, Galileo demonstrated this by dropping balls of iron and wood from the Leaning Tower of Pisa to show that they would fall together. Air resistance would have ruined the experiment, but a feather and a hammer dropped on the airless moon by an astronaut did fall together.
- ▶ Galileo stated the law of inertia: In the absence of friction, a moving body on a horizontal plane will continue moving forever.
- ▶ The first of Newton's three laws of motion was based on Galileo's law of inertia: A body continues at rest or in uniform motion in a straight line unless it is acted on by some force.
- ▶ **Momentum (p. 79)** is the tendency of a moving body to continue moving.
- ▶ **Mass (p. 79)** is the amount of matter in a body.
- ▶ Newton's second law says that an **acceleration (p. 79)** (a change in velocity) must be caused by a force. A **velocity (p. 79)** is a directed speed, so a change in speed or direction is an acceleration.
- ▶ Newton's third law says that forces occur in pairs acting in opposite directions.
- ▶ Newton realized that the curved path of the moon meant that it was being accelerated toward Earth and away from a straight-line path. That required the presence of a force—gravity.

- ▶ From his mathematical analysis, Newton was able to show that the force of gravity between two masses is proportional to the product of their masses and obeys the **inverse square law (p. 81)**. That is, the force of gravity is inversely proportional to the square of the distance between the two objects.
- ▶ To explain how gravity can act at a distance, scientists describe it as a **field (p. 81)**.
- ▶ An object in space near Earth would move along a straight line and quickly leave Earth were it not for Earth's gravity accelerating the object toward Earth's center and forcing it to follow a curved path, an orbit. Objects in orbit around Earth are falling (being accelerated) toward Earth's center. If there is no friction, the object will fall around its orbit forever.
- ▶ An object in a **closed orbit (p. 85)** follows an elliptical path. A circle is just a special case of an ellipse with zero eccentricity. To follow a circular orbit, an object must orbit with **circular velocity (p. 84)**. At a certain distance from Earth, a **geosynchronous satellite (p. 84)** stays above a spot on Earth's equator as Earth rotates.
- ▶ If a body's velocity equals or exceeds the **escape velocity, V_e (p. 85)**, it will follow a parabola or hyperbola. These orbits are termed **open orbits (p. 85)** because the object never returns to its starting place.
- ▶ Two objects in orbit around each other actually orbit their common **center of mass (p. 85)**.
- ▶ Newton's laws explain Kepler's three laws of planetary motion. The planets follow elliptical orbits because gravity obeys the inverse square law. The planets move faster when closer to the sun and slower when farther away because they conserve **angular momentum (p. 83)**. A planet's orbital period squared is proportional to its orbital radius cubed because the moving planet conserves energy.
- ▶ **Energy (p. 86)** refers to the ability to produce a change. **Kinetic energy (p. 86)** is an object's energy of motion, and **potential energy (p. 86)** is the energy an object has because of its position in a gravitational field. The unit of energy is the **joule (J) (p. 86)**.
- ▶ Tides are caused by differences in the force of gravity acting on different parts of a body. Tides on Earth occur because the moon's gravity pulls more strongly on the near side of Earth than on the center of Earth, and more strongly on the center of Earth than on the far side of Earth. As a result, there are two tidal bulges on Earth caused by the moon's gravity, one toward the moon on Earth's near side and one away from the moon on Earth's far side.
- ▶ Tides produced by the moon combine with tides produced by the sun to cause extreme tides (called **spring tides (p. 87)**) at new and full moons. The moon and sun work against each other to produce smallest tides (**neap tides (p. 87)**) at quarter moons.
- ▶ Friction from tides can slow the rotation of a rotating world, and the gravitational pull of tidal bulges can make orbits change slowly.
- ▶ Einstein published two theories that extended Newton's laws of motion and gravity, the special theory of relativity and the general theory of relativity.
- ▶ **Special theory of relativity (p. 91)** says that uniform (unaccelerated) motion is relative. Observers cannot detect their uniform motion through space except relative to outside objects. This is known as the first postulate. This leads to the second postulate: The speed of light is a constant for all observers.
- ▶ A consequence of special relativity is that mass and energy are related.
- ▶ The **general theory of relativity (p. 92)** says that a gravitational field is a curvature of space-time caused by the presence of a mass. For example, Earth's mass curves space-time, and the mass of your body responds to that curvature by accelerating toward Earth's center.
- ▶ The curvature of space-time was confirmed by the slow advance in perihelion (precession) of the orbit of Mercury, and by the deflection of starlight passing near the sun observed during a 1919 total solar eclipse.

Review Questions

1. Why wouldn't Aristotle's explanation of gravity work if Earth is not the center of the universe?
2. According to the principles of Aristotle, what part of the motion of a baseball pitched across the home plate is natural motion? What part is violent motion?
3. If you drop a feather and a steel hammer at the same moment, they should hit the ground at the same instant. Why doesn't this work on Earth, and why does it work on the moon?
4. What is the difference between mass and weight? Between speed and velocity?
5. Why did Newton conclude that some force had to pull the moon toward Earth?
6. Why did Newton conclude that gravity has to be mutual and universal?
7. How does the concept of a field explain action at a distance? Name another kind of field also associated with action at a distance.
8. Why can't a spacecraft go "beyond Earth's gravity?"
9. What is the center of mass of the Earth-moon system? Where is it?
10. How do planets orbiting the sun, and skaters doing a spin, both conserve angular momentum?
11. Why is the period of an open orbit undefined?
12. How does the first postulate of special relativity imply the second?
13. When you ride a fast elevator upward, you feel slightly heavier as the trip begins and slightly lighter as the trip ends. How is this phenomenon related to the equivalence principle?
14. From your knowledge of general relativity, would you expect radio waves from distant galaxies to be deflected as they pass near the sun? Why or why not?
15. **How Do We Know?** Why would science be impossible if some natural events happened without causes?
16. **How Do We Know?** Why is it important that a theory make testable predictions?

Discussion Questions

1. How did Galileo idealize his inclines to conclude that an object in motion stays in motion until it is acted on by some force?
2. Give an example from everyday life to illustrate each of Newton's laws.
3. People who lived before Newton may not have believed in cause and effect as strongly as you do. How do you suppose that affected how they saw their daily lives?

Problems

1. Compared with the strength of Earth's gravity at its surface, how much weaker is gravity at a distance of 10 Earth radii from Earth's center? At 20 Earth radii?
2. Compare the force of lunar gravity on the surface of the moon with the force of Earth's gravity at Earth's surface.
3. If a small lead ball falls from a high tower on Earth, what will be its velocity after 2 seconds? After 4 seconds?
4. What is the circular velocity of an Earth satellite 1000 km above Earth's surface? (*Hint:* Earth's radius is 6380 km.)
5. What is the circular velocity of an Earth satellite 36,000 km above Earth's surface? What is its orbital period? (*Hint:* Earth's radius is 6380 km.)
6. What is the orbital period of an imaginary satellite orbiting just above Earth's surface? Ignore friction with the atmosphere.
7. Repeat the previous problem for Mercury, Venus, the moon, and Mars. (*Hint:* Find the masses and radii of each of these objects in the Appendix A tables.)

8. Describe the orbit followed by the slowest cannonball on page 84 on the assumption that the cannonball could pass freely through Earth. (Newton got this problem wrong the first time he tried to solve it.)
9. If you visited an asteroid 30 km in radius with a mass of 4.0×10^{17} kg, what would be the circular velocity at its surface? A major league fastball travels about 90 mph. Could a good pitcher throw a baseball into orbit around the asteroid?
10. What is the orbital period of a satellite orbiting just above the surface of the asteroid in Problem 9?
11. What would be the escape velocity at the surface of the asteroid in Problem 9? Could a major league pitcher throw a baseball off of the asteroid?

2. Why is it a little bit misleading to say that this astronaut is weightless?



MASA/JSC

Learning to Look

1. Why can the object shown below be bolted in place and used 24 hours a day without adjustment?



Larry Muvehill/The Image Works

6

Light and Telescopes



Guidepost

In the early chapters of this book, you looked at the sky the way ancient astronomers did, with the unaided eye. In the last chapter, you got a glimpse through Galileo's telescope, and it revealed amazing things about the moon, Jupiter, and Venus. Now it is time to examine the instruments of the modern astronomer.

You can begin by studying telescopes that gather and focus visible light, so you need to be sure you understand what light is and how it behaves. But you will quickly meet telescopes that gather invisible forms of radiation such as X-rays and radio waves. Astronomers cannot overlook any clues, so they must use all forms of light. This chapter will help you answer five essential questions:

— **What is light?**

— **How do telescopes work, and how are they limited?**

— **What kind of instruments do astronomers use to record and analyze light?**

— **Why do astronomers use radio telescopes?**

— **Why must some telescopes go into space?**

Astronomy is almost entirely an observational science. Astronomers cannot visit distant galaxies and far-off worlds, so they must observe using astronomical telescopes. Twenty chapters remain in your exploration, and every one will discuss information gathered by telescopes.

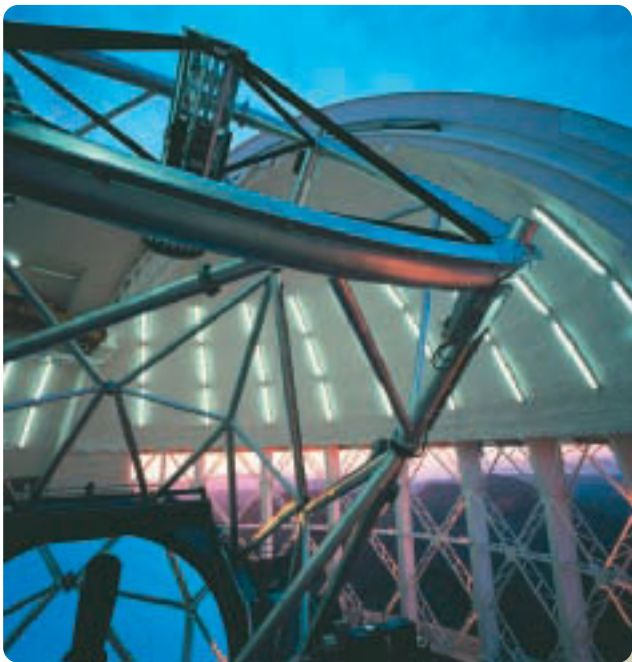
Astronomers go to extremes to build giant telescopes atop high mountains, where they are above most of the distortion caused by Earth's atmosphere.
(Mauna Kea Observatory)

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STARLIGHT IS GOING TO WASTE. Every night it falls on trees, oceans, and parking lots, and it is all wasted. To an astronomer, nothing is so precious as starlight. It is the only strong link to the universe, so the astronomer's quest is to gather as much of it as possible and extract from it the secrets of the heavens.

The telescope is the symbol of the astronomer because it gathers and concentrates light for analysis. Most of the interesting objects in the sky are faint, so astronomers are driven to build huge telescopes to gather the maximum amount of light (■ Figure 6-1). Some telescopes collect radio waves or X-rays, and some go into space, but they all gather information about our universe.

In the quotation that opens this chapter, Robert Frost suggests that someone in every town should own a telescope. Astronomy is more than technology and scientific analysis. It helps tell us what we are, and every town should have a telescope to keep us looking upward.



■ **Figure 6-1**

Astronomical telescopes are often very large to gather large amounts of starlight. The Southern Gemini telescope stands over 19 m (60 ft) high when pointed straight up, and its main mirror, shown at lower left, is 8.1 m (26.5 ft) in diameter—larger than some classrooms. The sides of the telescope dome open to allow quick equalization of inside and outside temperatures at sunset. (Gemini Observatory/Aura)

6-1 Radiation: Information from Space

JUST AS A BOOK ON BAKING BREAD might begin with a discussion of flour, this chapter on telescopes begins with a discussion of light—not just visible light, but the entire range of radiation from the sky.

Light as a Wave and a Particle

When you admire the colors of a rainbow, you are seeing light behave as a wave. But when you use a digital camera to take a picture of the same rainbow, the light hitting the camera's detector acts like a particle. Light is peculiar in that it is both wave and particle, and how it acts depends on how you observe it.

Light is a form of **electromagnetic radiation** and carries energy through space as electric and magnetic waves. We use the word *light* to refer to electromagnetic radiation that we can see, but visible light is only a small part of a larger range that includes X-rays and radio waves. Electromagnetic radiation travels through space at 300,000 km/s (186,000 mi/s). This is commonly referred to as the speed of light, c , but it is in fact the speed of all electromagnetic radiation.

Some people flinch at the word *radiation*, but that reflects a **Common Misconception**. *Radiation* refers to anything that radiates from a source. High-energy particles emitted from radioactive atoms are called radiation, and you have learned to be a little bit concerned when you see this word. But light, like all electromagnetic radiation, spreads outward from a source, so you can correctly refer to light as a form of radiation.

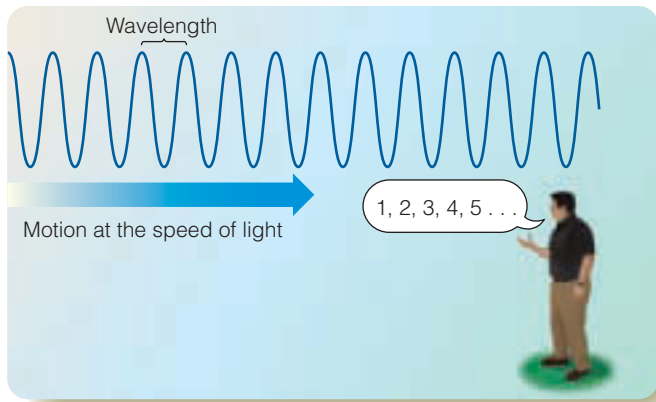
Electromagnetic radiation can act as a wave phenomenon—that is, it is associated with a periodically repeating disturbance, a wave. You are familiar with waves in water: If you disturb a pool of water, waves spread across the surface. Imagine that you use a meter stick to measure the distance between the successive peaks of a wave. This distance is the **wavelength**, usually represented by the Greek letter lambda (λ).

Wavelength is related to **frequency**, the number of waves that pass a stationary point in 1 second (■ Figure 6-2). Wavelength and frequency are related, and you can calculate the wavelength by dividing the speed of light by the frequency.

$$\lambda = \frac{c}{f}$$

When you tune in your favorite FM station at, say, 89.5 on the dial, which means 89.5 MHz (million cycles per second), you are adjusting your radio to detect radio waves with a wavelength of 3.35 m. Note that the higher the frequency, the shorter the wavelength.

Sound is another example of a wave, in that case a mechanical disturbance that travels through air from source to ear. Sound requires a medium; so, on the moon, where there is no air, there can be no sound. In contrast, light is made up of electric and magnetic fields that can travel through empty space. Unlike sound,



■ **Figure 6-2**

All electromagnetic waves travel at the speed of light. The wavelength is the distance between successive peaks. The frequency of the wave is the number of peaks that pass you in one second.

light does not require a medium, and so it can travel through a perfect vacuum. There is no sound on the moon, but there is plenty of sunlight. There is a **Common Misconception** that radio waves are related to sound. Actually, radio waves are a type of light, electromagnetic radiation that your radio converts into sound so you can listen. Radio communication works just fine between astronauts standing on the moon.

Although electromagnetic radiation can behave as a wave, it can also behave as a flood of particles. A particle of electromagnetic radiation is called a **photon**, and you can think of a photon as a bundle of waves.

The amount of energy a photon carries depends inversely on its wavelength. That is, shorter-wavelength photons carry more energy, and longer-wavelength photons carry less. A simple formula expresses this relationship:

$$E = \frac{hc}{\lambda}$$

Here h is Planck's constant (6.63×10^{-34} joule s), c is the speed of light (3.00×10^8 m/s), and λ is the wavelength in meters. This book will not use this formula for calculations; the important point is the inverse relationship between the energy E and the wavelength λ . As λ gets smaller, E gets larger. A photon of long wavelength carries a very small amount of energy, but a photon with a very short wavelength can carry much more energy.

The Electromagnetic Spectrum

A **spectrum** is an array of electromagnetic radiation displayed in order of wavelength. You are most familiar with the spectrum of visible light, which you see in rainbows. The colors of the visible spectrum differ in wavelength, with red having the longest wavelength and violet the shortest. The visible spectrum is shown at the top of ■ Figure 6-3.

The average wavelength of visible light is about 0.0005 mm. You could put roughly 50 light waves end to end across the

thickness of a sheet of household plastic wrap. It is awkward to describe such short distances in millimeters, so scientists give the wavelength of light using **nanometer (nm)** units, equal to one-billionth of a meter (10^{-9} m). Another unit that astronomers commonly use is called the **angstrom (Å)** (named after the Swedish astronomer Anders Jonas Ångström). One angstrom is 10^{-10} m, one-tenth of a nanometer. The wavelength of visible light ranges from about 400 to 700 nm (4000 to 7000 Å). Just as you sense the wavelength of sound as pitch, you sense the wavelength of light as color. Light near the short-wavelength end of the visible spectrum (400 nm) looks violet to your eyes, and light near the long-wavelength end (700 nm) looks red.

Figure 6-3 shows that the visible spectrum makes up only a small part of the entire electromagnetic spectrum. Beyond the red end of the visible spectrum lies **infrared radiation**, where wavelengths range from 700 nm to about 1 mm. Your eyes are not sensitive to this radiation, but your skin senses it as heat. A “heat lamp” warms you by giving off infrared radiation.

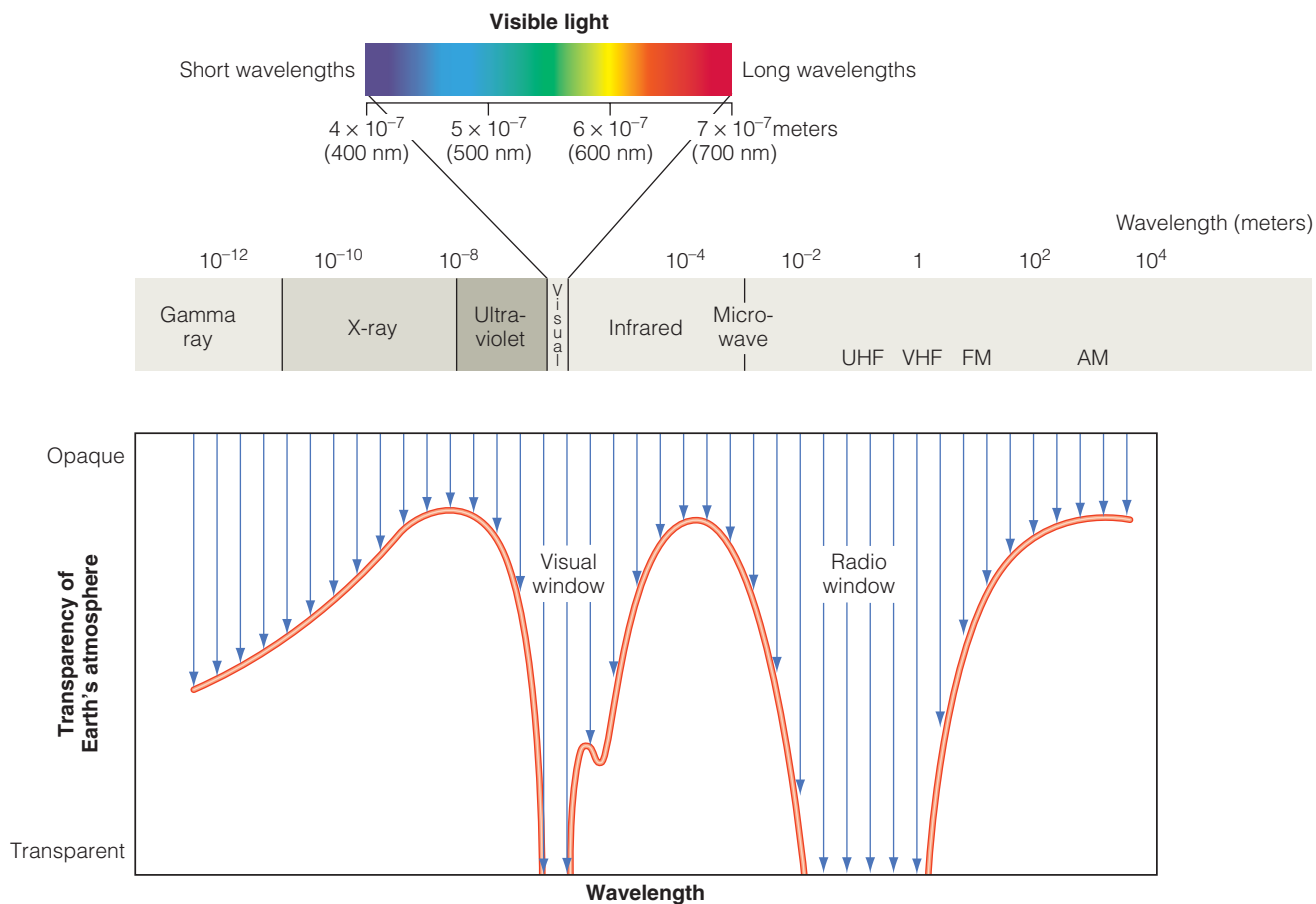
Beyond the infrared part of the electromagnetic spectrum lie radio waves. The radio radiation used for AM radio transmissions has wavelengths of a few kilometers down to a few hundred meters, while FM, television, military, government, cell phone, and ham radio transmissions have wavelengths that range down to a few centimeters. Microwave transmission, used for radar and some long-distance telephone communications as well as for cooking food in a microwave oven, has wavelengths from a few centimeters down to about 1 mm.

The boundaries between the sections of the spectrum are not sharply defined. Long-wavelength infrared radiation blends smoothly into the shortest microwave radio waves. Similarly, there is no natural division between the short-wavelength infrared and the long-wavelength part of the visible spectrum.

Now look at the other end of the electromagnetic spectrum in Figure 6-3 and notice that electromagnetic waves shorter than violet are called **ultraviolet**. Electromagnetic waves that are even shorter are called X-rays, and the shortest are gamma rays. Again, the boundaries between these wavelength ranges are defined only by conventional usage, not by natural divisions.

Recall the formula for the energy of a photon. Extremely short-wavelength photons such as X-rays and gamma rays have high energies and can be dangerous. Even ultraviolet photons have enough energy to do you harm. Small doses of ultraviolet produce a suntan, and larger doses cause sunburn and skin cancers. Contrast this to the lower-energy infrared photons. Individually they have too little energy to affect skin pigment, a fact that explains why you can't get a tan from a heat lamp. Only by concentrating many low-energy photons in a small area, as in a microwave oven, can you transfer significant amounts of energy.

Astronomers are interested in electromagnetic radiation from space because it carries clues to the nature of stars, planets, and other celestial objects. Earth's atmosphere is opaque to most electromagnetic radiation, as shown in the graph at the bottom



■ **Figure 6-3**

The spectrum of visible light, extending from red to violet, is only part of the electromagnetic spectrum. Most radiation is absorbed in Earth's atmosphere, and only radiation in the visual window and the radio window can reach Earth's surface.

of Figure 6-3. Gamma rays, X-rays, and some radio waves are absorbed high in Earth's atmosphere, and a layer of ozone (O_3) at altitudes of about 15–30 km absorbs ultraviolet radiation. Water vapor in the lower atmosphere absorbs the longer-wavelength infrared radiation. Only visible light, some shorter-wavelength infrared, and some radio waves reach Earth's surface through two wavelength regions called **atmospheric windows**. Obviously, if you wish to study the sky from Earth's surface, you must look out through one of these windows.

SCIENTIFIC ARGUMENT

What would you see if your eyes were sensitive only to X-rays?

Sometimes the best way to understand a concept is to build a scientific argument and change one factor so you must imagine a totally new situation. In this case, you might at first expect to be able to see through walls, but remember that your eyes detect only light that already exists. There are almost no X-rays bouncing around at Earth's surface, so if you had X-ray eyes, you would be in the dark and would be unable to see anything. Even when you looked up at the sky, you would see nothing, because Earth's atmosphere is not transparent to X-rays. If Superman can see through walls, it is not because his eyes can detect X-rays.

But now imagine a slightly different situation and modify your argument. **Would you be in the dark if your eyes were sensitive only to radio wavelengths?**

6-2 Optical Telescopes

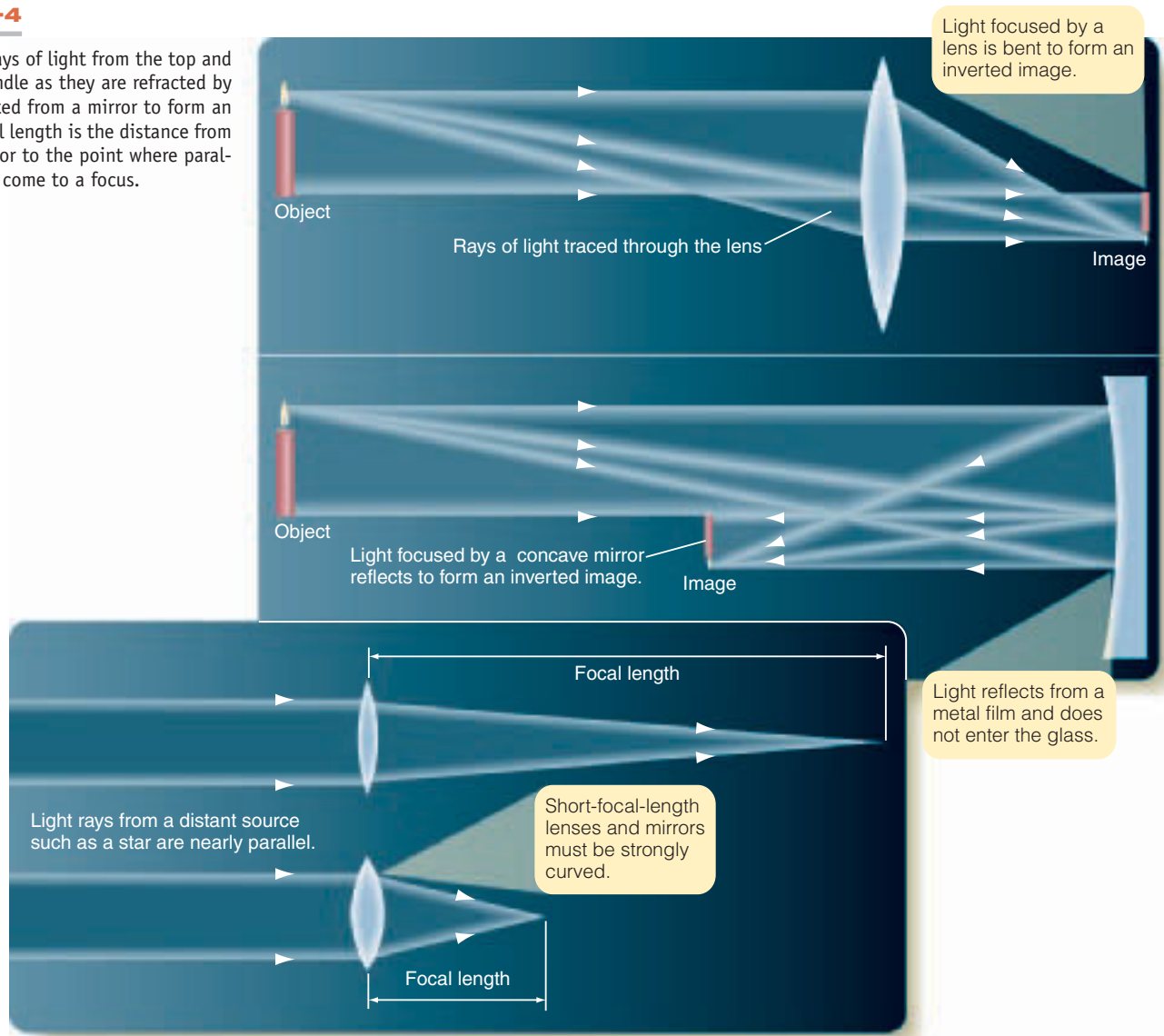
EARTH HAS TWO ATMOSPHERIC WINDOWS, so there are two main types of ground-based telescopes—optical telescopes and radio telescopes. You can start with optical telescopes, which gather light and focus it into sharp images. This requires sophisticated optical and mechanical designs, and it leads astronomers to build gigantic telescopes on the tops of high mountains.

Two Kinds of Optical Telescopes

Optical telescopes can focus light into an image by using either a lens or a mirror, as shown in ■ Figure 6-4. In a **refracting telescope**, the **primary** (or **objective**) **lens** bends (refracts) the light as it passes through the glass and brings it to a focus to form a small inverted image. In a **reflecting telescope**, the **primary**

■ **Figure 6-4**

You can trace rays of light from the top and bottom of a candle as they are refracted by a lens or reflected from a mirror to form an image. The focal length is the distance from the lens or mirror to the point where parallel rays of light come to a focus.



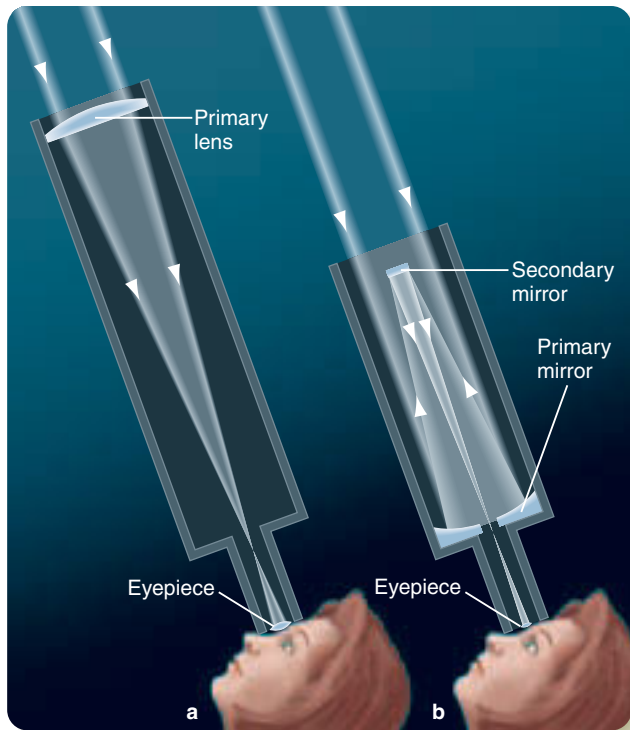
(or **objective**) **mirror**—a concave piece of glass with a reflective surface—forms an image by reflecting the light. In either case, the **focal length** is the distance from the lens or mirror to the image of a distant light source such as a star. Short-focal-length lenses and mirrors must be strongly curved, and long-focal-length lenses and mirrors are less strongly curved. Grinding the proper shape on a lens or mirror is a delicate, time-consuming, and expensive process.

The image formed by the primary lens or primary mirror of a telescope is small, inverted, and difficult to view directly. Astronomers use a small lens called the **eyepiece** to magnify the image and make it convenient to view (■ Figure 6-5).

Refracting telescopes suffer from a serious optical distortion that limits their usefulness. When light is refracted through glass, shorter wavelengths bend more than longer wavelengths, so blue light, for example, having shorter wavelengths, comes to a focus closer to the lens than does red light (■ Figure 6-6a). That means

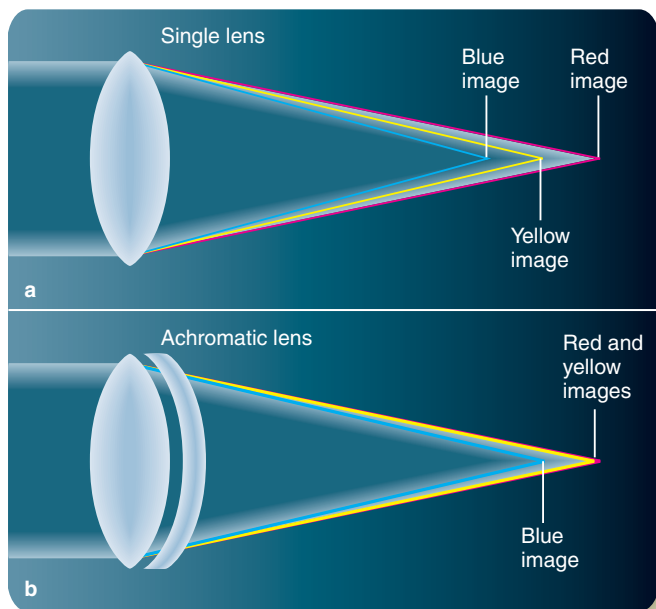
if you focus the eyepiece on the blue image, the other colors are out of focus, and you see a colored blur around the image. If you focus on the red image, all the other colors blur. This color separation is called **chromatic aberration**. Telescope designers can grind a telescope lens of two components made of different kinds of glass and so bring two different wavelengths to the same focus (Figure 6-6b). This does improve the image, but these **achromatic lenses** are not totally free of chromatic aberration. Even though two colors have been brought together, the other wavelengths still blur. Telescopes made with achromatic lenses were popular until the end of the 19th century.

The primary lens of a refracting telescope is more expensive than a mirror of the same size. The lens must be achromatic, so it must be made of two different kinds of glass with four precisely ground surfaces. Also, the glass must be pure and flawless because the light passes through it. The largest refracting telescope in the world was completed in 1897 at Yerkes Observatory in Wisconsin.



■ **Figure 6-5**

(a) A refracting telescope uses a primary lens to focus starlight into an image that is magnified by a lens called an eyepiece. The primary lens has a long focal length, and the eyepiece has a short focal length. (b) A reflecting telescope uses a primary mirror to focus the light by reflection. A small secondary mirror reflects the starlight back down through a hole in the middle of the primary mirror to the eyepiece.



■ **Figure 6-6**

(a) A normal lens suffers from chromatic aberration because short wavelengths bend more than long wavelengths. (b) An achromatic lens, made in two pieces of two different kinds of glass, can bring any two colors to the same focus, but other colors remain slightly out of focus.

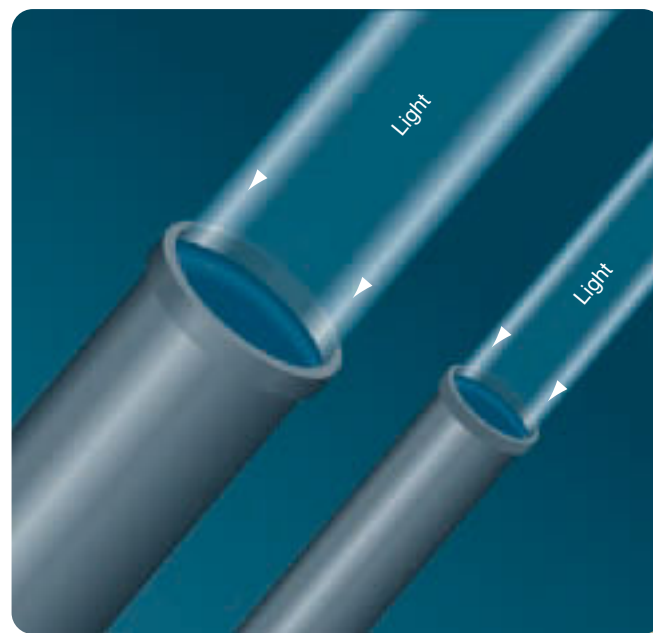
Its lens is 1 m (40 in.) in diameter and weighs half a ton. Larger refracting telescopes are prohibitively expensive.

The primary mirrors of reflecting telescopes are much less expensive because the light reflects off the front surface of the mirror. This means that only the front surface needs to be ground to precise shape. This front surface is coated with a highly reflective surface of an aluminum alloy, and the light reflects from this front surface without entering the glass. Consequently, the glass of the mirror need not be perfectly transparent, and the mirror can be supported over its back surface to reduce sagging. Most important, reflecting telescopes do not suffer from chromatic aberration because the light is reflected before it enters the glass. For these reasons, every large astronomical telescope built since the beginning of the 20th century has been a reflecting telescope.

The Powers of a Telescope

Astronomers build large telescopes because a telescope can aid your eyes in three ways—the three powers of a telescope—and the two most important of these powers depends on the diameter of the telescope.

Nearly all of the interesting objects in the sky are faint sources of light, so astronomers need telescopes that can gather large amounts of light to produce bright images. **Light-gathering power** refers to the ability of a telescope to collect light. Catching light in a telescope is like catching rain in a bucket—the bigger the bucket, the more rain it catches (■ Figure 6-7). Light-gathering power is proportional to the area of the telescope



■ **Figure 6-7**

Gathering light is like catching rain in a bucket. A large-diameter telescope gathers more light and has a brighter image than a smaller telescope of the same focal length.

objective. A lens or mirror with a large area gathers a large amount of light. The area of a circular lens or mirror is πr^2 , or, written in terms of the diameter, the area is $\pi(D/2)^2$. To compare the relative light-gathering powers (*LGP*) of two telescopes *A* and *B*, you can calculate the ratio of the areas of their objectives, which reduces to the ratio of their diameters (*D*) squared.

$$\frac{LGP_A}{LGP_B} = \left(\frac{D_A}{D_B}\right)^2$$

For example, suppose you compared a telescope 24 cm in diameter with a telescope 4 cm in diameter. The ratio of the diameters is 24/4, or 6, but the larger telescope does not gather six times as much light. Light-gathering power increases as the ratio of diameters squared, so it gathers 36 times more light than the smaller telescope. This example shows the importance of diameter in astronomical telescopes. Even a small increase in diameter produces a large increase in light-gathering power and allows astronomers to study much fainter objects.

The second power, **resolving power**, refers to the ability of the telescope to reveal fine detail. Because light acts as a wave, it produces a small **diffraction fringe** around every point of light in the image, and you cannot see any detail smaller than the fringe (■ Figure 6-8). Astronomers can't eliminate diffraction fringes, but the larger a telescope is in diameter, the smaller the diffraction fringes are. That means the larger the telescope, the better its resolving power.

If you consider only optical telescopes, you can estimate the resolving power by calculating the angular distance between two stars that are just barely visible through the telescope as two separate images. Astronomers say the two images are “resolved,” meaning they are separated from each other. The resolving power, α , in arc seconds, equals 11.6 divided by the diameter of the telescope in centimeters:

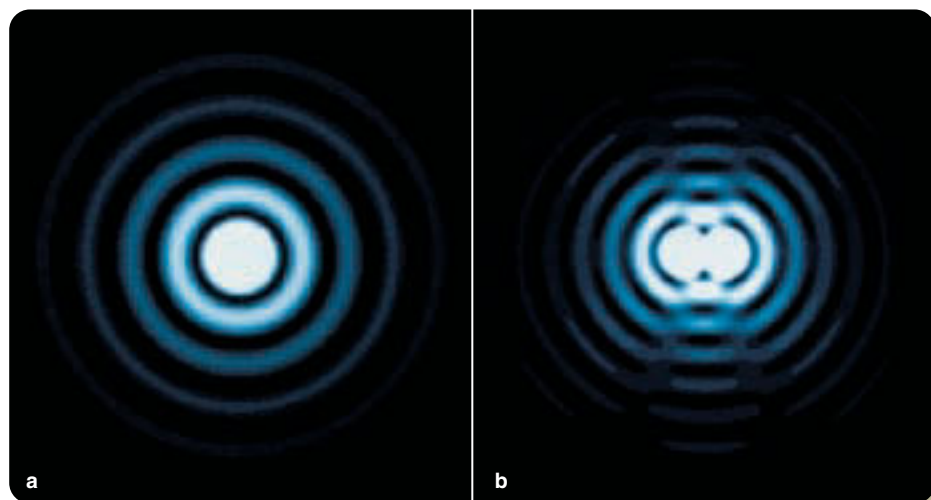
$$\alpha = \frac{11.6}{D}$$

For example, the resolving power of a 25.0 cm telescope is 11.6 divided by 25.0, or 0.46 arc seconds. No matter how perfect the telescope optics, this is the smallest detail you can see through that telescope.

This calculation gives you the best possible resolving power of a telescope of diameter *D*, but the actual resolution can be limited by two other factors—lens quality and atmospheric conditions. A telescope must contain high-quality optics to achieve its full potential resolving power. Even a large telescope reveals little detail if its optics are marred with imperfections. Also, when you look through a telescope, you are looking up through miles of turbulent air in Earth's atmosphere, which makes the image dance and blur, a condition called **seeing**. A related phenomenon is the twinkling of stars. The twinkles are caused by turbulence in Earth's atmosphere, and a star near the horizon, where you look through more air, will twinkle and blur more than a star overhead.

On a night when the atmosphere is unsteady, the images are blurred, and the seeing is bad (■ Figure 6-9). Even under good seeing conditions, the detail visible through a large telescope is limited, not by its diffraction fringes but by the air through which the telescope must look. A telescope performs better on a high mountaintop where the air is thin and steady, but even there Earth's atmosphere limits the detail the best telescopes can reveal to about 0.5 arc seconds. You will learn later in this chapter about telescopes that orbit above Earth's atmosphere and are not limited by seeing.

Seeing and diffraction limit the amount of information in an image, and that limits the accuracy of any measurement made based on that image. Have you ever tried to magnify a newspaper photo to distinguish some detail? Newspaper photos are made up of tiny dots of ink, and no detail smaller than a single dot will be visible no matter how much you magnify the photo. In an astronomical image, the resolution is often limited by seeing. You can't see a detail in the image that is smaller than the resolution.



■ **Figure 6-8**

(a) Stars are so far away that their images are points, but the wave nature of light surrounds each star image with diffraction fringes (much magnified in this computer model). (b) Two stars close to each other have overlapping diffraction fringes and become impossible to detect separately. (Computer model by M. A. Seeds)

Resolution and Precision

What limits the detail you can see in an image? All images have limited resolution. You see this on your computer screen because images there are made up of picture elements, pixels. If your screen has large pixels, the resolution is low, and you can't see much detail. In an astronomical image, the size of a picture element is set by seeing and by diffraction in the telescope. You can't see detail smaller than that resolution limit.

This limitation on the detail in an image is related to the limited precision of any measurement. Imagine a zoologist trying to measure the length of a live snake by holding it along a meter stick. The wriggling snake is hard to hold, so it is hard to measure accurately. Also, meter sticks are usually

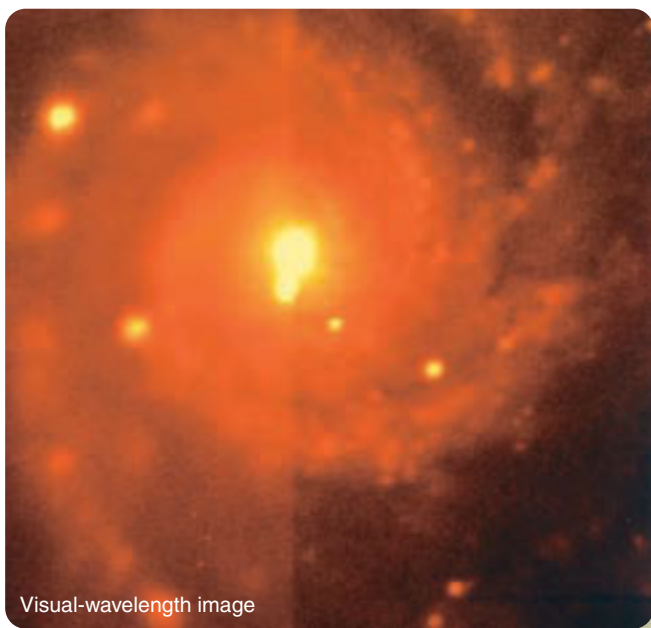
not marked finer than millimeters. Both factors limit the precision of the measurement. If the zoologist said the snake was 43.28932 cm long, you might be suspicious. The resolution of the measurement technique does not justify the accuracy implied by all those digits.

Whenever you make a measurement you should ask yourself how accurate that measurement can be. The accuracy of the measurement is limited by the resolution of the measurement technique, just as the amount of detail in a photograph is limited by its resolution. If you photographed a star, you would not be able to see details on its surface for the same reason the zoologist can't measure the snake to high precision.



A high-resolution image of Mars reveals details such as mountains, craters, and the southern polar cap. (NASA)

That's why stars look like fuzzy points of light no matter how big your telescope. All measurements have some built-in uncertainty (**How Do We Know? 6-1**), and scientists must learn to work within those limitations.



Visual-wavelength image

■ Figure 6-9

The left half of this photograph of a galaxy is from an image recorded on a night of poor seeing. Small details are blurred. The right half of the photo is from an image recorded on a night when Earth's atmosphere above the telescope was steady and the seeing was better. Much more detail is visible under good seeing conditions. (Courtesy William Keel)

It is a **Common Misconception** that the purpose of an astronomical telescope is to magnify the image. In fact, the **magnifying power** of a telescope, its ability to make the image bigger, is the least important of the three powers. Because the amount of detail you can see is limited by the seeing conditions and the resolving power, very high magnification does not necessarily show more detail. You can change the magnification by changing the eyepiece, but you cannot alter the telescope's light-gathering power or resolving power without changing the diameter of the objective lens or mirror, and that would be so expensive that you might as well build a whole new telescope.

You can calculate the magnification of a telescope by dividing the focal length of the objective by the focal length of the eyepiece:

$$M = \frac{F_o}{F_e}$$

For example, if a telescope has an objective with a focal length of 80 cm and you use an eyepiece whose focal length is 0.5 cm, the magnification is 80/0.5, or 160 times.

Notice that the two most important powers of the telescope, light-gathering power and resolving power, depend on the diameter of the telescope. This explains why astronomers refer to telescopes by diameter and not by magnification. Astronomers will refer to a telescope as an 8-meter telescope or a 10-meter telescope, but they would never identify a research telescope as being a 200-power telescope.

The quest for light-gathering power and high resolution explains why nearly all major observatories are located far from

big cities and usually on high mountains. Astronomers avoid cities because **light pollution**, the brightening of the night sky by light scattered from artificial outdoor lighting, can make it impossible to see faint objects (■ Figure 6-10a). In fact, many residents of cities are unfamiliar with the beauty of the night sky because they can see only the brightest stars. Even far from cities, nature's own light pollution, the moon, is sometimes so bright it drowns out fainter objects, and astronomers are often unable to observe on the nights near full moon. On such nights, faint objects cannot be detected even with the largest telescopes on high mountains.

Astronomers prefer to place their telescopes on carefully selected high mountains for a number of reasons. The air there is thin, very dry, and more transparent, especially in the infrared. For the best seeing, astronomers select mountains where

the air flows smoothly and is not turbulent. Building an observatory on top of a high mountain far from civilization is difficult and expensive, as you can imagine from the photo in Figure 6-10b, but the dark sky and steady seeing make it worth the effort.

Buying a Telescope

Thinking about how to shop for a new telescope will not only help you if you decide to buy one but will also illustrate some important points about astronomical telescopes.

Assuming you have a fixed budget, you should buy the highest-quality optics and the largest-diameter telescope you can afford. You can't make the atmosphere less turbulent, but you can choose good optics. If you buy a telescope from a toy store and it has plastic lenses, you shouldn't expect to see very

much. Also, you want to maximize the light-gathering power of your telescope, so you want to purchase the largest-diameter telescope you can afford. Given a fixed budget, that means you should buy a reflecting telescope rather than a refracting telescope. Not only will you get more diameter per dollar, but your telescope will not suffer from chromatic aberration.

You can safely ignore magnification. Department stores and camera shops may advertise telescopes by quoting their magnification, but it is not an important number. What you can see is determined by light-gathering power, optical quality, and Earth's atmosphere. You can change the magnification simply by changing eyepieces.

Other things being equal, you should choose a telescope with a solid mounting that will hold the telescope steady and allow you to point it at objects easily. Computer-controlled



■ **Figure 6-10**

(a) This satellite view of the continental United States at night shows the light pollution and energy waste produced by outdoor lighting. Observatories cannot be located near large cities. (NASA) (b) The domes of four giant telescopes are visible at upper left at Paranal Observatory, built by the European Southern Observatory. The Atacama Desert is believed to be the driest place on Earth. (ESO)

pointing systems are available for a price on many small telescopes. A good telescope on a poor mounting is almost useless.

You might be buying a telescope to put in your backyard, but you must think about the same issues astronomers consider when they design giant telescopes to get on mountaintops.

Observing Beyond the Ends of the Visible Spectrum

Telescopes in mountain-top observatories usually observe at visual wavelengths, but important observations also can be made from Earth at some infrared and ultraviolet wavelengths.

Beyond the red end of the visible spectrum, some infrared radiation leaks through the atmosphere in narrow, partially open atmospheric windows ranging from wavelengths of 1200 nm to about 20,000 nm. Infrared astronomers usually measure wavelength in micrometers (10^{-6} meters), so they refer to this wavelength range as 1.2 to 30 micrometers (or microns for short). Even in this range, much of the radiation from celestial sources is absorbed by water vapor, carbon dioxide, and ozone molecules. Nevertheless, some infrared observations can be made from mountaintops where the air is thin and dry. For example, a number of important infrared telescopes observe from the 4200-m (13,800-ft) summit of Mauna Kea in Hawaii. At this altitude, the telescopes are above much of the water vapor in Earth's atmosphere (■ Figure 6-11).

Infrared telescopes have flown to high altitudes under balloons and in airplanes to get above absorption by water vapor. NASA is now testing the Stratospheric Observatory for Infrared Astronomy (SOFIA), a Boeing 747SP that will carry a 2.5-m telescope, control systems, and a team of astronomers, technicians, and educators into the dry fringes of the atmosphere. Once at that altitude, they can open a door above the telescope and make infrared observations for hours as the plane flies a precisely calculated path. You can see the door in the photo in Figure 6-11.

To reduce internal noise, the light-sensitive detectors in astronomical telescopes are cooled to very low temperatures, usually with liquid nitrogen, as shown in Figure 6-11. This is especially necessary for a telescope observing at infrared wavelengths. Infrared radiation is emitted by heated objects, and if the telescope is warm it will emit many times more infrared radiation than that coming from a distant object. Imagine trying to look for something at night through binoculars that are themselves glowing.

Beyond the other end of the visible spectrum, astronomers can observe in the near-ultraviolet at wavelengths of about 290 to 400 nm. Your eyes don't detect this radiation, but it can be recorded by specialized detectors. Wavelengths shorter than about 290 nm, the far-ultraviolet, are completely absorbed by the ozone layer extending from about 15 km to 30 km above Earth's surface. No mountaintop is that high, and no airplane can fly to such an altitude. To observe in the far-ultraviolet or beyond at X-ray or gamma-ray wavelengths, telescopes must be in space above the atmosphere.



■ **Figure 6-11**

Comet Hale-Bopp hangs in the sky over the 3-meter NASA Infrared Telescope Facility (IRAF) atop Mauna Kea. The air at high altitudes is so dry that it is transparent to shorter infrared photons. SOFIA will fly at altitudes up to 14 km (45,000 feet) where it will be able to observe infrared wavelengths that cannot be observed from mountaintops. Most astronomical CCD cameras must be cooled to low temperatures, and this is especially true for infrared cameras. (IRTF: William Keel; SOFIA: NASA; Camera: Kris Koenig/Coast Learning Systems)

New-Generation Telescopes

For most of the 20th century, astronomers faced a serious limitation on the size of astronomical telescopes. Traditional telescope mirrors were made thick to avoid sagging that would distort the reflecting surface, but those thick mirrors were heavy. The 5-m (200-in.) mirror on Mount Palomar weighs 14.5 tons. These traditional telescopes were big, heavy, and expensive.

Today's astronomers have solved these problems in a number of ways. Read **Modern Astronomical Telescopes** on pages 110–111 and notice three important points about telescope design and ten new terms that describe astronomical telescopes and their operation:

- 1 Traditional telescopes use large, solid, heavy mirrors to focus starlight to a *prime focus*, or, by using a *secondary mirror*, to a *Cassegrain focus*. Some small telescopes have a *Newtonian focus* or a *Schmidt-Cassegrain focus*.
- 2 Telescopes must have a *sidereal drive* to follow the stars, and an *equatorial mounting* with easy motion around a *polar axis* is the traditional way to provide that motion. Today, astronomers can build simpler, lighter-weight telescopes on *alt-azimuth mountings* that depend on computers to move the telescope so that it follows the westward motion of the stars as Earth rotates.

- 3 **Active optics**, computer control of the shape of telescope mirrors, allows the use of thin, lightweight mirrors—either “floppy” mirrors or segmented mirrors. Reducing the weight of the mirror reduces the weight of the rest of the telescope and makes it stronger and less expensive. Also, thin mirrors cool faster at nightfall and produce better images.

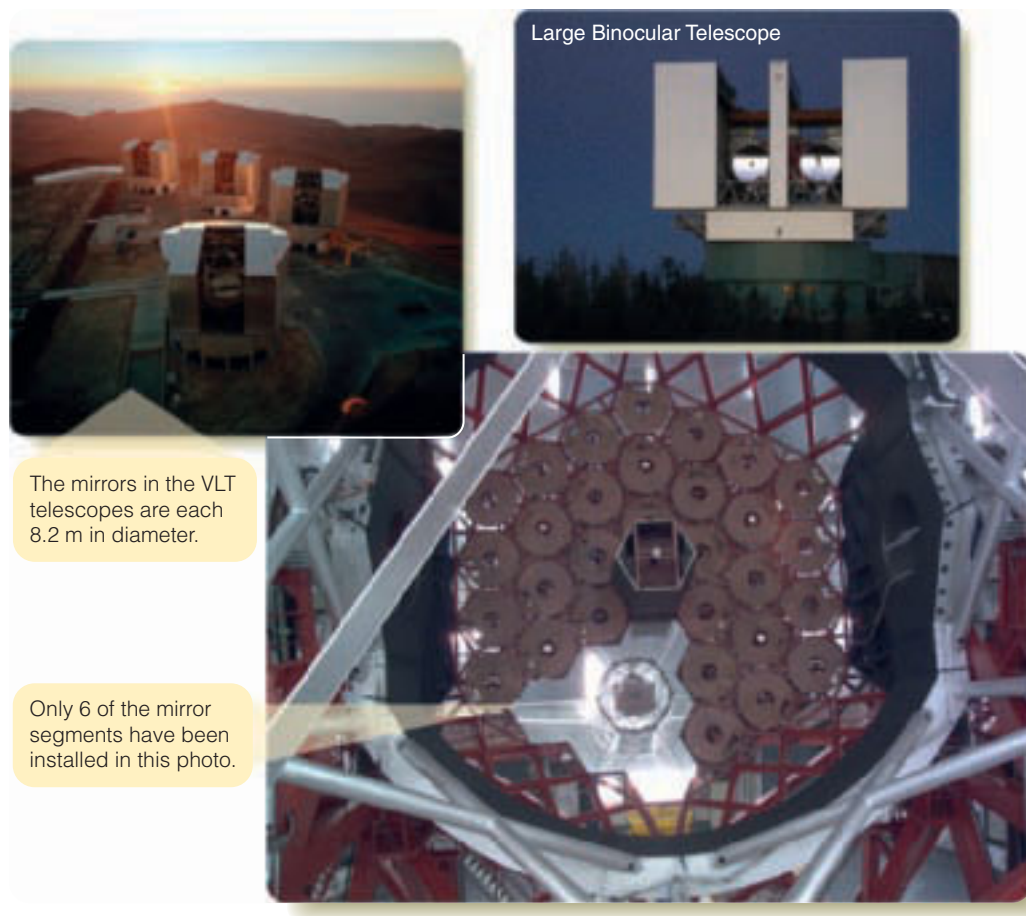
High-speed computers have allowed astronomers to build new, giant telescopes with unique designs. A few are shown in ■ Figure 6-12. The European Southern Observatory has built the Very Large Telescope (VLT) high in the remote Andes Mountains of northern Chile. The VLT actually consists of four telescopes, each with a computer-controlled mirror 8.2 m in diameter and only 17.5 cm (6.9 in.) thick. The four telescopes can work singly or can combine their light to work as one large telescope. Italian and American astronomers have built the Large Binocular Telescope, which carries a pair of 8.4-m mirrors on a single mounting. The Gran Telescopio Canarias, located atop a volcanic peak in the Canary Islands, carries a segmented mirror 10.4 meters in diameter and holds, for the moment, the record as the largest single telescope in the world.

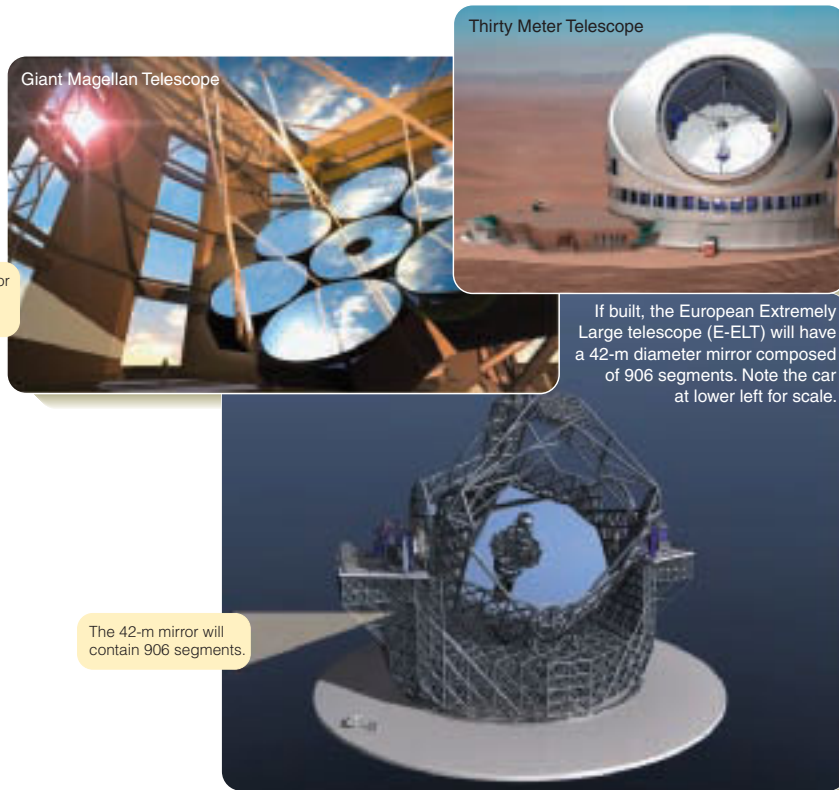
Other giant telescopes are being planned with segmented mirrors or with multiple mirrors (■ Figure 6-13). The Giant Magellan Telescope will carry seven thin mirrors, each 8.4 meters in diameter, on a single mounting. It will be located in the

Chilean Andes and is planned to have the light-gathering power of a 22-m telescope. The Thirty Meter Telescope, now under development by American astronomers, will have a mirror 30 meters in diameter, composed of 492 hexagonal segments. The European Extremely Large Telescope is being planned by an international team. It will carry 906 segments, making up a mirror 42 meters in diameter. Other very large telescopes are being proposed with completion dates of 2016 or later.

■ Figure 6-12

The four telescopes of the VLT are housed in separate domes at Paranal Observatory in Chile (Figure 6-10). The Large Binocular Telescope (LBT) carries two 8.4-m mirrors that combine their light. The entire building rotates as the telescope moves. The Gran Telescopio Canarias contains 36 hexagonal mirror segments in its 10.4-m primary mirror. (VLT: ESO; LBT: Large Binocular Telescope Project and European Industrial Engineer; GMT: ESO; GTC: Gara Mora, IAC)





■ **Figure 6-13**

The proposed Giant Magellan Telescope will have the resolving power of a telescope 24.5 meters in diameter when it is finished in about 2016. The Thirty Meter Telescope (TMT) is planned to occupy a specially designed dome. Like nearly all of the newest large telescopes, the European Extremely Large Telescope will be on an alt-azimuth mounting. (GMT: ESO; TMT: TMT; Thirty-Meter Telescope; E-ELT: ESO)

Adaptive Optics

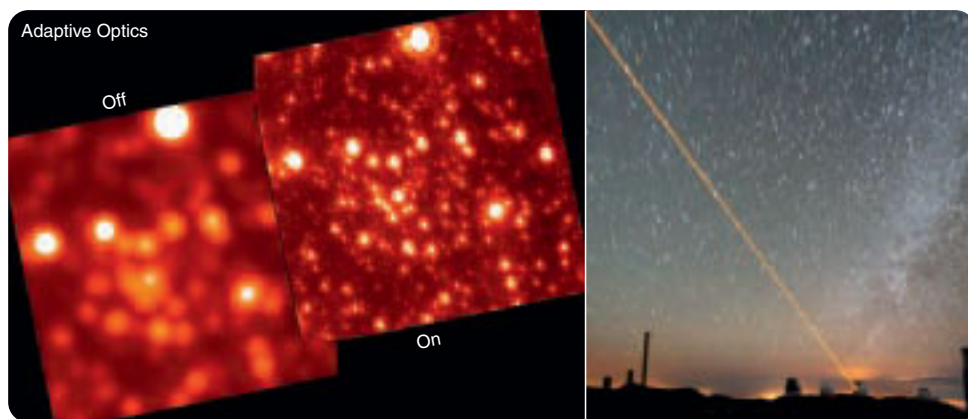
Not too many years ago, astronomers thought it was pointless to build more large telescopes on Earth's surface because of seeing distortion caused by the atmosphere. In the 1990s, computers became fast enough to allow astronomers to correct for some of that distortion, and that has made the new generation of giant telescopes possible.

Modern computers have revolutionized telescope design and operation. Nearly all large telescopes are operated by astronomers and technicians working at computers in a control room, and some telescopes can be operated by astronomers thousands of miles from the observatory. Some telescopes are fully automated and observe without direct human supervision. This has made possible huge surveys of the sky in which millions of objects are observed. The Sloan Digital Sky Survey, for example, mapped the sky, measuring the position and brightness of 100 million stars and galaxies at a number of wavelengths. The Two-Micron All Sky Survey (2MASS) has mapped the entire sky at three wavelengths in the infrared. Other surveys are being made at other wavelengths. Astronomers will study those data banks for decades to come.

Adaptive optics uses high-

speed computers to monitor the distortion produced by turbulence in Earth's atmosphere and then correct the telescope image to sharpen a fuzzy blob into a crisp picture. The resolution of the image is still limited by diffraction in the telescope, but removing much of the seeing distortion produces a dramatic improvement in the detail visible (■ Figure 6-14). Don't confuse adaptive optics with the slower-speed active optics that controls the overall shape of a telescope mirror.

To monitor the distortion in an image, adaptive optics systems must look at a fairly bright star in the field of view, and there isn't always such a star properly located near a target object such as a faint galaxy. In that case, astronomers can point a laser at a spot in the sky very close to their target object, and where the laser excites gas in Earth's upper atmosphere, it produces a glowing



■ **Figure 6-14**

In these images of the center of our galaxy, the adaptive optics system was turned off for the left image and on for the right image. Not only are the images of stars sharper, but because the light is focused into smaller images, fainter stars are visible. The laser beam shown leaving one of the Keck Telescopes produces an artificial star in the field of view, and the adaptive optics system uses the laser-produced point of light to reduce seeing distortion in the entire image. (left, CFHT; right, Paul Hirst)

Modern Astronomical Telescopes

1 The traditional telescopes described on this page are limited by complexity, weight, and Earth's atmosphere. Modern solutions are shown on the opposite page.

In larger telescopes the light can be focused to a **prime focus** position high in the telescope tube as shown at the right. Although it is a good place to image faint objects, the prime focus is inconvenient for large instruments.

A **secondary mirror** can reflect the light through a hole in the primary mirror to a **Cassegrain focus**. This focal arrangement may be the most common form of astronomical telescope.

The Cassegrain focus is convenient and has room for large instruments.

Secondary mirror

With the secondary mirror removed, the light converges at the prime focus. In large telescopes, astronomers can ride inside the prime-focus cage, although most observations are now made by instruments connected to computers in a separate control room.

Traditional mirrors are thick to prevent the optical surface from sagging and distorting the image as the telescope is moved around the sky. Large mirrors can weigh many tons and are expensive to make and difficult to support. Also, they cool slowly at nightfall. Expansion and contraction in the cooling mirror causes distortion in the images.

1a Smaller telescopes are often found with a **Newtonian focus**, the arrangement that Isaac Newton used in his first reflecting telescope. The Newtonian focus is inconvenient for large telescopes as shown at right.

Newtonian focus

Thin correcting lens

Schmidt-Cassegrain telescope

1b Many small telescopes such as the one on your left use a **Schmidt-Cassegrain focus**. A thin correcting plate improves the image but is too slightly curved to introduce serious chromatic aberration.

1c Shown below, the 4-meter Mayall Telescope at Kitt Peak National Observatory in Arizona can be used at either the prime focus or the Cassegrain focus. Note the human figure at lower right.

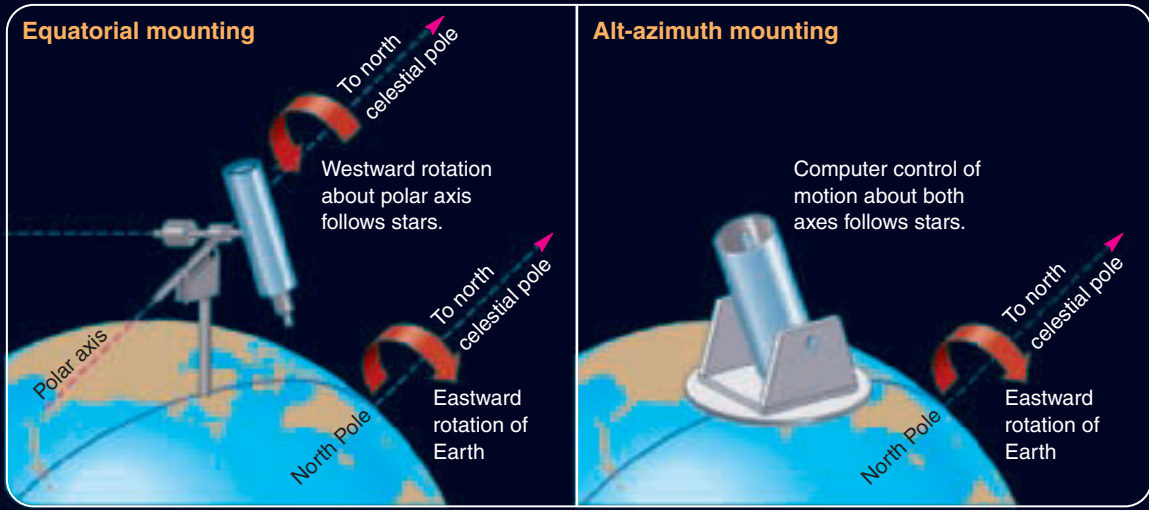
Prime focus cage

Secondary mirror

Primary mirror (inside)

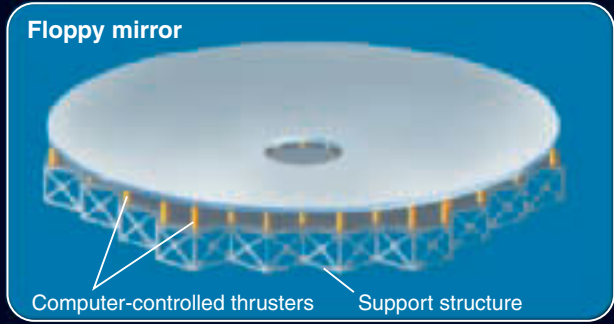
Cassegrain focus

Astronomer



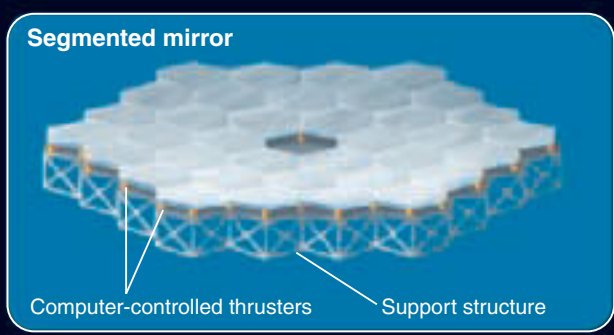
2 Telescope mountings must contain a **sidereal drive** to move smoothly westward and counter the eastward rotation of Earth. The traditional **equatorial mounting** (far left) has a **polar axis** parallel to Earth's axis, but the modern **alt-azimuth mounting** (near left) moves like a cannon — up and down and left to right. Such mountings are simpler to build but need computer control to follow the stars.

3 Unlike traditional thick mirrors, thin mirrors, sometimes called floppy mirrors as shown at right, weigh less and require less massive support structures. Also, they cool rapidly at nightfall and there is less distortion from uneven expansion and contraction.

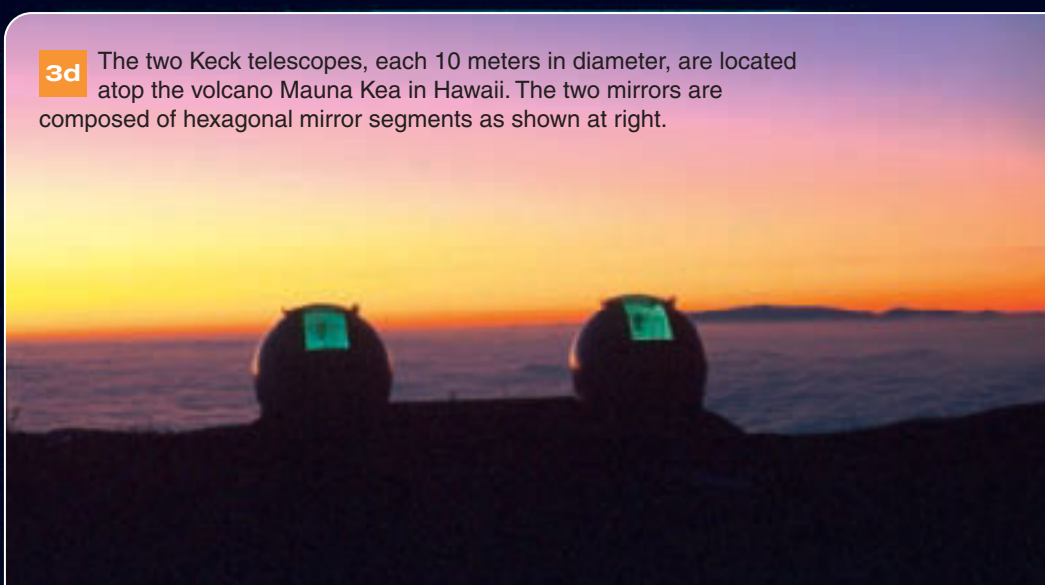


3a Grinding a large mirror may remove tons of glass and take months, but new techniques speed the process. Some large mirrors are cast in a rotating oven that causes the molten glass to flow to form a concave upper surface. Grinding and polishing such a preformed mirror is much less time consuming.

3b Mirrors made of segments are economical because the segments can be made separately. The resulting mirror weighs less and cools rapidly. See image at right.



3c Both floppy mirrors and segmented mirrors sag under their own weight. Their optical shape must be controlled by computer-driven thrusters under the mirror in what is called **active optics**.



3d The two Keck telescopes, each 10 meters in diameter, are located atop the volcano Mauna Kea in Hawaii. The two mirrors are composed of hexagonal mirror segments as shown at right.



W.M. Keck Observatory

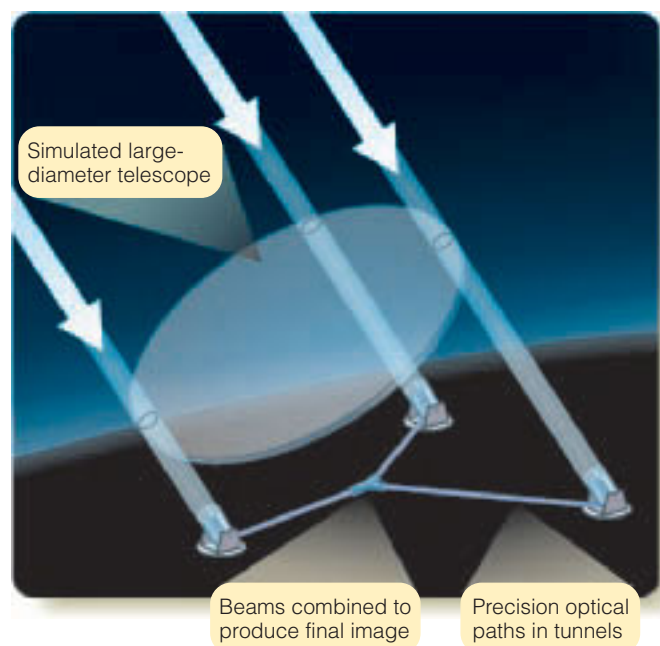
artificial star in the field of view. The adaptive optics system can use the artificial star to correct the image of the fainter target.

Today astronomers are planning huge optical telescopes composed of segmented mirrors tens of meters in diameter. Those telescopes would be almost useless without adaptive optics.

Interferometry

One of the reasons astronomers build big telescopes is to increase resolving power, and astronomers have been able to achieve very high resolution by connecting multiple telescopes together to work as if they were a single telescope. This method of synthesizing a larger telescope is known as **interferometry** (■ Figure 6-15). One expert said, “We combine the light from separate telescopes and fool the waves into thinking they were collected by one big ‘scope.” The images from such a virtual telescope are not limited by the diffraction fringes of the individual small telescopes but rather by the diffraction fringes of the much larger virtual telescope.

In an interferometer, the light from the separate telescopes must be combined as if it had been collected by a single large mirror. That means that a network of small, high-precision mirrors must bring the light beams together, and the path that each light beam travels must be controlled so that it does not vary more than a small fraction of the wavelength. Turbulence in Earth’s atmosphere constantly distorts the light, and high-speed computers must continuously adjust the light paths. Recall that



■ **Figure 6-15**

In an astronomical interferometer, smaller telescopes can combine their light through specially designed optical tunnels to simulate a larger telescope with a resolution set by the separation of the smaller telescopes.

the wavelength of light is very short, roughly 0.0005 mm, so building optical interferometers is one of the most difficult technical problems that astronomers face. Infrared- and radio-wavelength interferometers are slightly easier to build because the wavelengths are longer. In fact, as you will discover later in this chapter, the first astronomical interferometers were built by radio astronomers.

The VLT shown in Figure 6-12 consists of four 8.2-m telescopes that can operate separately but can also be linked together through underground tunnels with three 1.8-m telescopes on the same mountaintop. The resulting optical interferometer provides the resolution (but, of course, not the light gathering power) of a telescope 200 meters in diameter. Other telescopes, such as the two Keck 10-m telescopes, can work as interferometers. The CHARA array on Mt. Wilson combines six 1-meter telescopes to create the resolving power equivalent of a telescope one-fifth of a mile in diameter. The Large Binocular Telescope shown in Figure 6-12 can be used as an interferometer.

Although turbulence in Earth’s atmosphere can be partially averaged out in an interferometer, plans are being made to put interferometers in space to avoid atmospheric turbulence altogether. The Space Interferometry Mission, for example, will work at visual wavelengths and study everything from the cores of erupting galaxies to planets orbiting nearby stars.

SCIENTIFIC ARGUMENT

Why do astronomers build observatories at the tops of mountains?

Measurement accuracy is so important that scientists often take extreme steps to gather accurate information. It certainly isn’t easy to build a large, delicate telescope at the top of a high mountain, but it is worth the effort. A telescope on top of a high mountain is above the densest part of Earth’s atmosphere. There is less air to dim the light, and there is less water vapor to absorb infrared radiation. Even more important, the thin air on a mountaintop causes less disturbance to the image, and consequently the seeing is better. A large telescope on Earth’s surface has a resolving power much better than the distortion caused by Earth’s atmosphere. So, it is limited by seeing, not by its own diffraction. It really is worth the trouble to build telescopes atop high mountains.

Astronomers not only build telescopes on mountaintops, they also build gigantic telescopes many meters in diameter. Revise your argument to focus on telescope design. **What are the problems and advantages in building such giant telescopes?**

6-3 Special Instruments

JUST LOOKING THROUGH A TELESCOPE doesn’t tell you much. A star looks like a point of light. A planet looks like a little disk. A galaxy looks like a hazy patch. To use an astronomical telescope to learn about the universe, you must be able to analyze the light the telescope gathers. Special instruments attached to the telescope make that possible.

Imaging Systems

The original imaging device in astronomy was the photographic plate. It could record images of faint objects in long time exposures and could be stored for later analysis. But photographic plates have been almost entirely replaced by electronic imaging systems.

Most modern astronomers use **charge-coupled devices (CCDs)** to record images. A CCD is a specialized computer chip containing millions of microscopic light detectors arranged in an array about the size of a postage stamp. Although CCDs for astronomy are extremely sensitive and therefore expensive, less sophisticated CCDs are used in video and digital cameras. Not only can CCD chips replace photographic plates, but they have some dramatic advantages. They can detect both bright and faint objects in a single exposure, are much more sensitive than photographic plates, and can be read directly into computer memory for later analysis.

You can easily sharpen and enhance images from your digital camera because the image from a CCD is stored as numbers in computer memory. Astronomers can also manipulate images to bring out otherwise invisible details. Astronomers can produce **false-color images** in which different colors represent different levels of intensity and are not related to the true colors of the object. Or they can use false colors to represent different wavelengths not otherwise visible to the human eye, as in ■ Figure 6-16. False-color images are so useful they are commonly used in many other fields, such as medicine and meteorology.

In the past, measurements of intensity and color were made using specialized light meters attached to a telescope or on photographic plates. Today, nearly all such measurements are made more easily and more accurately with CCD images.

The Spectrograph

To analyze light in detail, astronomers need to spread the light out according to wavelength to form a spectrum, a task performed by a **spectrograph**. You can understand how this instrument works if you imagine reproducing an experiment performed by Isaac Newton in 1666. Newton bored a small hole in the window shutter of his bedroom to admit a thin beam of sunlight. When he placed a prism in the beam, it spread the light into a beautiful spectrum that splashed across his bedroom wall. From this and related experiments Newton concluded that white light is made of a mixture of all the colors.

Light passing through a prism is bent at an angle that depends on its wavelength. Violet (short wavelength) bends most, red (long wavelength) least, so the white light is spread into a spectrum (■ Figure 6-17). You could build a simple spectrograph using a prism to spread the light and a lens to guide the light into a camera.

Nearly all modern spectrographs use a grating in place of a prism. A **grating** is a piece of glass with thousands of microscopic

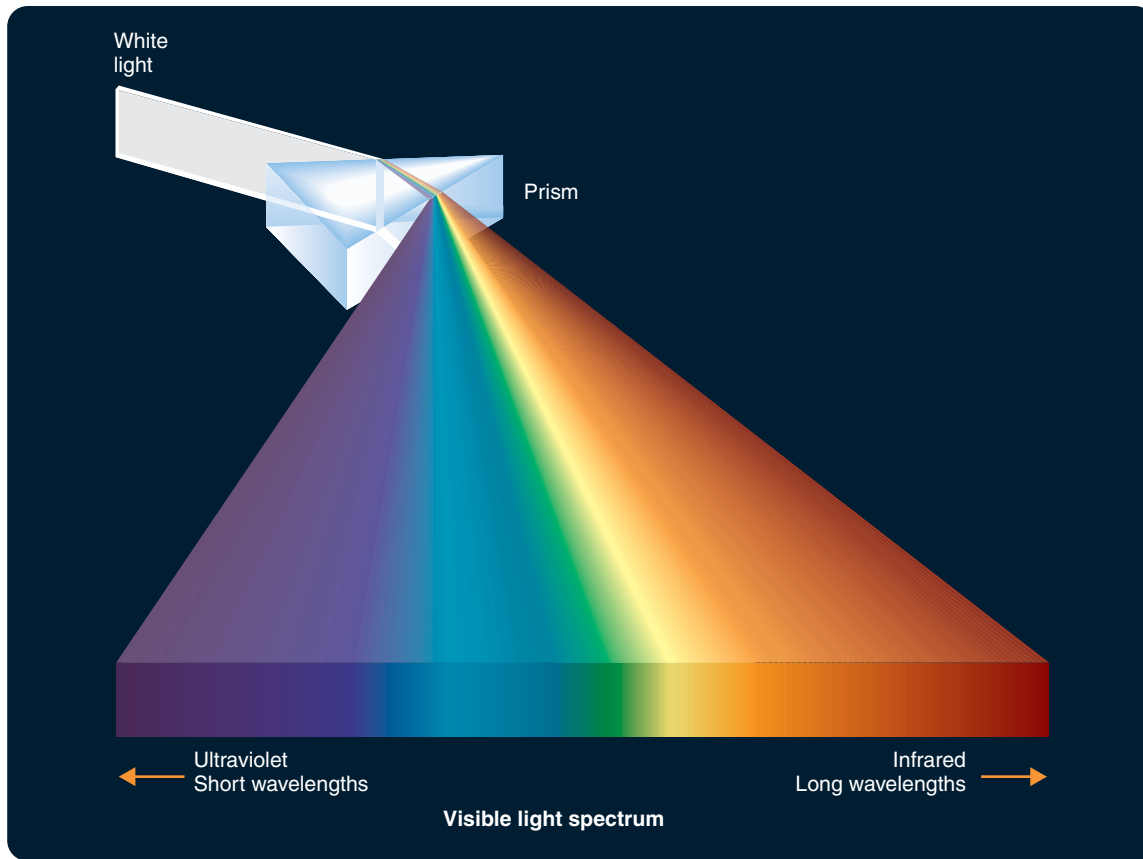


■ **Figure 6-16**

(a) The Sombrero Galaxy is 29 million light-years from Earth and contains many billions of stars. This visual wavelength image shows the clouds of dust in its disk. (NASA, Hubble Heritage Team; STScI/AURA) (b) This infrared image is reproduced in false color to show different wavelengths of infrared emission. Red represents the longest wavelengths and blue the shortest. (NASA/JPL-Caltech, Hubble Heritage Team; STScI/AURA)

parallel grooves scribed onto its surface. Different wavelengths of light reflect from the grating at slightly different angles, so white light is spread into a spectrum. You have probably noticed this effect when you look at the closely spaced lines etched onto a compact disk; as you tip the disk, different colors flash across its surface. You could build a modern spectrograph by using a high-quality grating to spread light into a spectrum and a CCD camera to record the spectrum.

The spectrum of an astronomical object can contain hundreds of **spectral lines**—dark or bright lines that cross the spectrum at specific wavelengths. The sun's spectrum, for instance, contains hundreds of dark spectral lines produced by the atoms in the sun's hot gases. To measure the precise wavelengths of individual lines and identify the atoms that produced them, astronomers use a **comparison spectrum** as a calibration. Special bulbs built into the spectrograph produce bright lines given off by such atoms as thorium, argon, or neon. The wavelengths of these spectral lines have been measured to high precision in the laboratory, so astronomers can use spectra of these light sources as guides to measure wavelengths and identify spectral lines in the spectrum of a star, galaxy, or planet.



■ **Figure 6-17**

A prism bends light by an angle that depends on the wavelength of the light. Short wavelengths bend most and long wavelengths least. Thus, white light passing through a prism is spread into a spectrum.

Because astronomers understand how light interacts with matter, a spectrum carries a tremendous amount of information, and that makes a spectrograph the astronomer's most powerful instrument. In the next chapter, you will learn more about the information astronomers can extract from a spectrum. An astronomer once remarked, "We don't know anything about an object till we get a spectrum," and that is only a slight exaggeration.

6-4 Radio Telescopes

CELESTIAL OBJECTS such as clouds of gas and erupting stars emit radio energy, and astronomers on Earth can study such objects by observing at wavelengths in the radio window where Earth's atmosphere is transparent to radio waves (see Figure 6-3). You might think an erupting star would produce a strong radio signal, but the signals arriving on Earth are astonishingly weak—a million to a billion times weaker than the signal from an FM radio station. Detecting such weak signals calls for highly sensitive equipment.

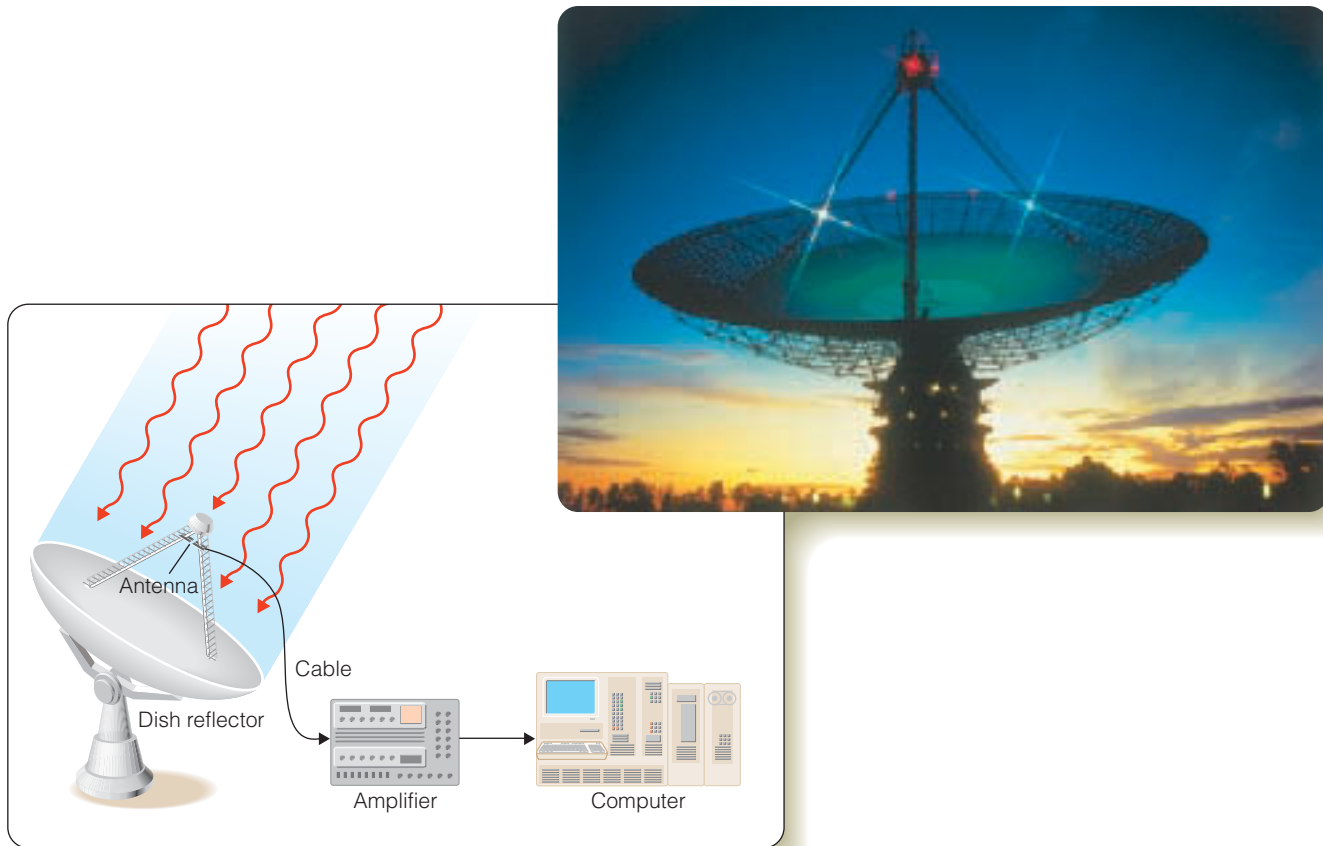
The Operation of a Radio Telescope

A radio telescope usually consists of four parts: a dish reflector, an antenna, an amplifier, and a recorder (■ Figure 6-18). These components, working together, make it possible for astronomers to detect radio radiation from celestial objects.

The dish reflector of a radio telescope, like the mirror of a reflecting telescope, collects and focuses radiation. Because radio waves are much longer than light waves, the dish need not be as smooth as a mirror; wire mesh will reflect all but the shortest wavelength radio waves.

Though a radio telescope's dish may be many meters in diameter, the antenna may be as small as your hand. Like the antenna on a TV set, its only function is to absorb the radio energy collected by the dish. Because the radio energy from celestial objects is so weak, it must be strongly amplified before it can be measured and its strength is recorded in computer memory.

Radio telescopes do not produce images. A single observation with a radio telescope measures the amount of radio energy coming from a specific point on the sky. So the radio telescope



■ **Figure 6-18**

In most radio telescopes, a dish reflector concentrates the radio signal on the antenna. The signal is then amplified and recorded. For all but the shortest radio waves, wire mesh is an adequate reflector.

must be scanned over an object to produce a map of the radio intensity at different points. Such radio maps are usually represented using contours to mark areas of similar radio intensity, much like a weather map where contours filled with color indicate areas of precipitation (■ Figure 6-19).

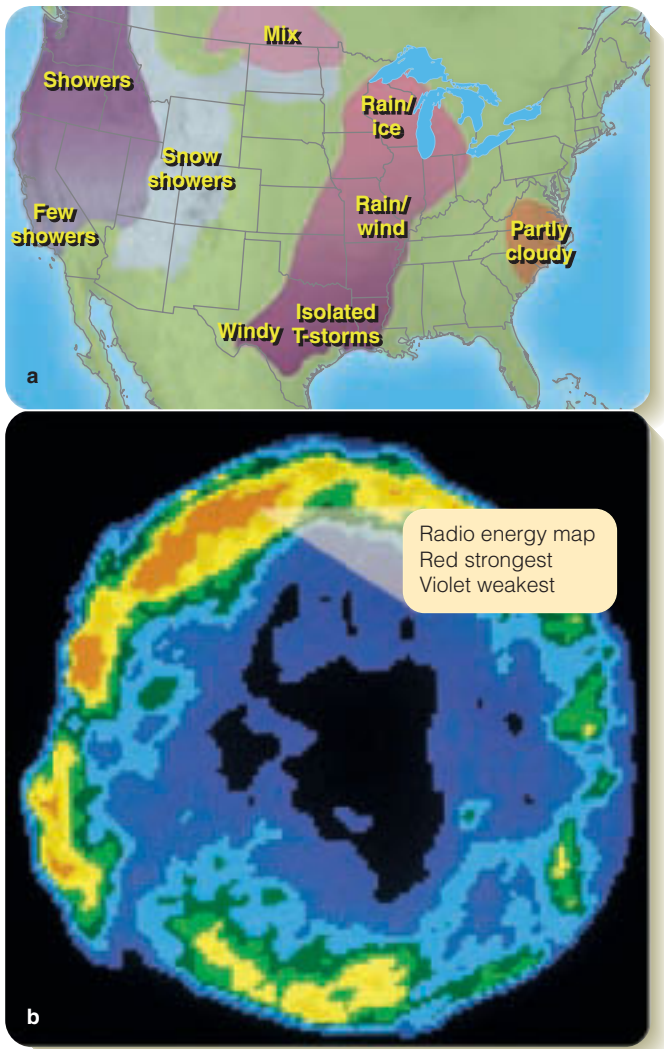
Limitations of a Radio Telescope

A radio astronomer works under three handicaps: poor resolution, low intensity, and interference. Recall that the resolving power of an optical telescope depends on the diameter of the objective lens or mirror. It also depends on the wavelength of the radiation because, at very long wavelengths like those of radio waves, the diffraction fringes are very large. That means a radio map can't show fine detail. As with an optical telescope, there is no way to improve the resolving power without building a bigger telescope. Consequently, radio telescopes generally have large diameters to minimize the diffraction fringes.

Even so, the resolving power of a radio telescope is not good. A dish 30 m in diameter receiving radiation with a wavelength of 21 cm has a resolving power of about 0.5° . Such a radio telescope would be unable to detect any details in the sky smaller than the

moon. Fortunately, radio astronomers can combine two or more radio telescopes to form a **radio interferometer** capable of much higher resolution. Just as in the case of optical interferometers, the radio astronomer combines signals from two or more widely separated dishes and “fools the waves” into behaving as if they were collected by a much bigger radio telescope.

Radio interferometers can be quite large. The Very Large Array (VLA) consists of 27 dish antennas spread in a Y-shape across the New Mexico desert (■ Figure 6-20). In combination, they have the resolving power of a radio telescope 36 km (22 mi) in diameter. The VLA can resolve details smaller than 1 arc second. Eight new dish antennas being added across New Mexico will give the VLA ten times better resolving power. Another large radio interferometer, the Very Long Baseline Array (VLBA), consists of matched radio dishes spread from Hawaii to the Virgin Islands and has an effective diameter almost as large as Earth. The Allen Telescope Array being built in California will eventually include 350 separate radio dishes. Radio astronomers are now planning the Square Kilometer Array, which will contain a huge number of radio dishes totaling a square kilometer of collecting area and spread to a diameter of at least 6000 kilometers. These



■ **Figure 6-19**

(a) A typical weather map uses contours with added color to show which areas are likely to receive precipitation. (b) A false-color-image radio map of Tycho's supernova remnant, the expanding shell of gas produced by the explosion of a star in 1572. The radio contour map has been color-coded to show intensity. (Courtesy NRAO)

giant radio interferometers depend on state-of-the-art, high-speed computers to combine signals and create radio maps.

The second handicap radio astronomers face is the low intensity of the radio signals. You learned earlier that the energy of a photon depends on its wavelength. Photons of radio energy have such long wavelengths that their individual energies are quite low. To get detectable signals focused on the antenna, the radio astronomer must build large collecting areas either as single large dishes or arrays of smaller dishes.

The largest fully steerable radio telescope in the world is at the National Radio Astronomy Observatory in Green Bank, West Virginia (■ Figure 6-21a). The telescope has a reflecting surface 100 meters in diameter, big enough to hold an entire football field, and can be pointed anywhere in the sky. Its surface consists of 2004 computer-controlled panels that adjust to maintain the shape of the reflecting surface.

The largest radio dish in the world is 300 m (1000 ft) in diameter. So large a dish can't be supported in the usual way, so it is built into a mountain valley in Arecibo, Puerto Rico. The reflecting dish is a thin metallic surface supported above the valley floor by cables attached near the rim, and the antenna hangs above the dish on cables from three towers built on three mountain peaks that surround the valley (Figure 6-21b). By moving the antenna above the dish, radio astronomers can point the telescope at any object that passes within 20 degrees of the zenith as Earth rotates. Since completion in 1963, the telescope has been an international center of radio astronomy research.

The third handicap the radio astronomer faces is interference. A radio telescope is an extremely sensitive radio receiver listening to faint radio signals. Such weak signals are easily drowned out by interference that includes everything from poorly designed transmitters in Earth satellites to automobiles with faulty ignition systems. A few narrow radio bands in the electromagnetic spectrum are reserved for radio astronomy, but even those are often contaminated by radio noise. To avoid interference, radio astronomers locate their telescopes as far from civilization as possible. Hidden deep in mountain valleys, they are able to listen to the sky protected from human-made radio noise.



■ **Figure 6-20**

(a) The Very Large Array uses 27 radio dishes, which can be moved to different positions along a Y-shaped set of tracks across the New Mexico desert. They are shown here in the most compact arrangement. Signals from the dishes are combined to create very-high-resolution radio maps of celestial objects. (NRAO) (b) The proposed Square Kilometer Array will have a concentration of detectors and radio dishes near its center with more dishes scattered up to 3000 km away. (Xilostudios/SKA Program Development Office)



■ **Figure 6-21**

(a) The largest steerable radio telescope in the world is the GBT located in Green Bank, West Virginia. With a diameter of 100 m, it stands higher than the Statue of Liberty. (Mike Bailey: NRAO/AUII) (b) The 300-m (1000-ft) radio telescope in Arecibo, Puerto Rico, hangs from cables over a mountain valley. The Arecibo Observatory is part of the National Astronomy and Ionosphere Foundation operated by Cornell University and the National Science Foundation. (David Parker/Science Photo Library)

Advantages of a Radio Telescope

Building large radio telescopes in isolated locations is expensive, but three factors make it all worthwhile. First, and most important, a radio telescope can reveal where clouds of cool hydrogen and other atoms and molecules are located. These clouds are important because, for one thing, they are the places where stars are born. Although cool clouds of gas are completely invisible to normal telescopes because they produce no visible light of their own and reflect too little to be detected in photographs, some gas atoms and molecules do emit radio photons. Cool hydrogen, for example, emits radio energy at the specific wavelength of 21 cm. (You will see how the hydrogen produces this radiation when you learn about the gas clouds in space in Chapter 10.) Other gas molecules emit radio energy with their own characteristic wavelengths. The only way astronomers can detect these clouds is with a radio telescope.

Another reason radio telescopes are important is related to dust in space. Astronomers observing at visual wavelengths can't see through the dusty clouds in space. Light waves are so short that they are scattered by the tiny dust grains and never get through the dust to reach optical telescopes on Earth. However, radio signals have wavelengths much longer than the diameters of dust grains, so radio waves from far across the galaxy pass

unhindered, giving radio astronomers an unobscured view. (The same is also true, to a large extent, of infrared radiation.)

Finally, radio telescopes are important because they can detect objects that are more luminous at radio wavelengths than at visible wavelengths. This includes, for example, intensely hot gas orbiting black holes. Some of the most violent events in the universe are detectable at radio wavelengths.

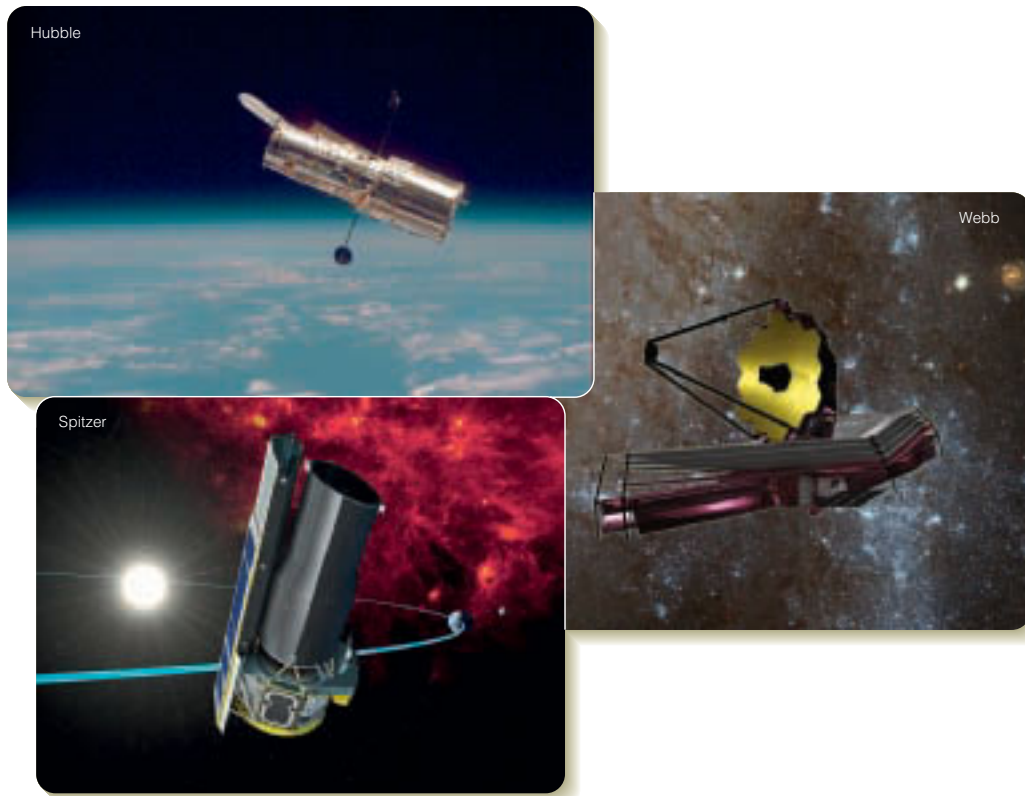
6-5 Astronomy from Space

YOU HAVE LEARNED about the observations that ground-based telescopes can make through the two atmospheric windows in the visible and radio parts of the electromagnetic spectrum. Most of the rest of the electromagnetic radiation—infrared, ultraviolet, X-ray, and gamma ray—never reaches Earth's surface; it is absorbed high in Earth's atmosphere. To observe at these wavelengths, telescopes must go above the atmosphere.

The Hubble Space Telescope

Named after Edwin Hubble, the astronomer who discovered the expansion of the universe, the Hubble Space Telescope is the most successful telescope ever to orbit Earth (■ Figure 6-22). It was launched in 1990 and contains a 2.4-m (95-in.) mirror with which it can observe visible, near-ultraviolet, and near-infrared light. It is controlled from a research center on Earth and observes continuously. Nevertheless, the telescope has time to complete only a fraction of the projects proposed by astronomers from around the world.

Most of the observations Hubble makes are at visual wavelengths, so its greatest advantage in being above Earth's



■ **Figure 6-22**

The Hubble Space Telescope orbits Earth only 569 km (353 mi) above the surface. Here it is looking to the upper left. The James Webb Space Telescope, planned to replace Hubble, will be over six times larger in collecting area. It will not have a tube but will observe from behind a sun screen. The infrared Spitzer Space Telescope orbits the sun slightly more slowly than Earth and gradually falls behind as it uses up its liquid helium coolant. (NASA/JPL-Caltech)

atmosphere is the lack of seeing distortion. It can detect fine detail, and, because it concentrates light into sharp images, it can see faint objects.

The telescope is as big as a large bus and has been visited a number of times by the space shuttle so that astronauts can maintain its equipment and install new cameras and spectrographs. Astronomers hope that it will last until it is replaced by the James Webb Space Telescope expected to launch no sooner than 2013. The Webb telescope will carry a cluster of beryllium segments that will open to form a 6.5-m (256-in.) mirror once in space.

Infrared Astronomy from Orbit

Telescopes that observe in the far-infrared must be protected from heat and must get above Earth's absorbing atmosphere. They have limited lifetimes because they must carry coolant to chill their optics. The Infrared Astronomical Satellite (IRAS) was a joint project of the United Kingdom, the United States, and the Netherlands. IRAS was launched in January of 1983 and carried liquid helium coolant to keep its telescope cold. It made 250,000 observations and, for example, discovered disks of dust around stars where planets are now thought to have formed. Its coolant ran out after 300 days of observation.

The most sophisticated of the infrared telescopes put in orbit, the Spitzer Space Telescope, like IRAS, is cooled to -269°C (-452°F). Launched in 2003, it observes from behind a

sunscreen. In fact, it could not observe from Earth orbit because Earth is such a strong source of infrared radiation, so the telescope was sent into an orbit around the sun that will carry it slowly away from Earth as its coolant is used up. Named after theoretical physicist Lyman Spitzer Jr. who originally suggested that space telescopes would be useful, it has made important discoveries concerning star formation, planets orbiting other stars, distant galaxies, and more.

High-Energy Astrophysics

High-energy astrophysics refers to the use of X-ray and gamma-ray observations of the sky. Making such observations is difficult but can reveal the secrets of processes such as the explosive deaths of massive stars and eruptions of supermassive black holes.

The first astronomical satellite, Ariel 1, was launched by British astronomers in 1962 and made solar observations in the ultraviolet and X-ray part of the spectrum. Since then many space telescopes have made high-energy observations from orbit. Some of these satellites have been general-purpose telescopes that can observe many different kinds of objects. ROSAT, for example, was an X-ray observatory developed by an international consortium of European astronomers. Some space telescopes are designed to study a single problem or a single object. The Japanese satellite Hinode, for example, studies the sun continuously at visual, ultraviolet, and X-ray wavelengths.



■ **Figure 6-23**

From space, the Chandra X-Ray Observatory recorded an X-ray image of galaxy M101. It is superimposed here on a visual wavelength image from the Hubble Space Telescope and an infrared image from the Spitzer Space Telescope. Blue shows hot gas around newborn stars, while red shows cool, dusty clouds of gas. (X-ray: NASA/CSC/JHU/K. Kuntz et al.; Optical: NASA/ESA/STScI/JHU/K. Kuntz et al.; IR: NASA/JPL-Caltech/STScI/K. Gordon)

The largest X-ray telescope to date, the Chandra X-ray Observatory, was launched in 1999. Chandra orbits a third of the way to the moon and is named for the late Indian-American Nobel laureate Subrahmanyan Chandrasekhar, who was a pioneer in many branches of theoretical astronomy. Focusing X-rays is difficult because they penetrate into most mirrors, so astronomers devised cylindrical mirrors in which the X-rays reflect from the polished inside of the cylinders and form images on special detectors. The telescope has made important discoveries about everything from star formation to monster black holes in distant galaxies (■ Figure 6-23) that will be described in later chapters.

One of the first gamma-ray observatories was the Compton Gamma Ray Observatory, launched in 1991. It mapped the entire sky at gamma-ray wavelengths. The European INTEGRAL

satellite was launched in 2002 and has been very productive in the study of violent eruptions of stars and black holes. The GLAST (Gamma-Ray Large Area Space Telescope), launched in 2008, is capable of mapping large areas of the sky to high sensitivity.

Modern astronomy has come to depend on observations that cover the entire electromagnetic spectrum. More orbiting space telescopes are planned that will be more versatile and more sensitive.

Cosmic Rays

All of the radiation you have read about in this chapter has been electromagnetic radiation, but there is another form of energy raining down from space, and scientists aren't sure where it comes from. **Cosmic rays** are subatomic particles traveling through space at tremendous velocities. Almost no cosmic rays reach the ground, but they do smash gas atoms in the upper atmosphere, and fragments of those atoms shower down on you day and night over your entire life. These secondary cosmic rays are passing through you as you read this sentence.

Some cosmic-ray research can be done from high mountains or high-flying aircraft; but, to study cosmic rays in detail, detectors must go into space. A number of cosmic-ray detectors have been carried into orbit, but this area of astronomical research is just beginning to bear fruit.

Astronomers can't be sure what produces cosmic rays. Because they are atomic particles with electric charges, they are deflected by the magnetic fields spread through our galaxy, and that means astronomers can't tell where their original sources are located. The space between the stars is a glowing fog of cosmic rays. Some lower-energy cosmic rays come from the sun, and observations show that at least some high-energy cosmic rays are produced by the violent explosions of dying stars and by supermassive black holes at the centers of galaxies.

At present, cosmic rays largely remain an exciting mystery. You will meet them again in future chapters.

What Are We? Curious

Telescopes are creations of curiosity. You look through a telescope to see more and to understand more. The unaided eye is a limited detector, and the history of astronomy is the history of bigger and better telescopes gathering more and more light to search for fainter and more distant objects.

The old saying, "Curiosity killed the cat," is an insult to the cat and to curiosity. We

humans are curious, and curiosity is a noble trait—the mark of an active, inquiring mind. At the limits of human curiosity lies the fundamental question, "What are we?" Telescopes extend and amplify our senses, but they also extend and amplify our curiosity about the universe around us.

When people find out how something works, they say their curiosity is *satisfied*.

Curiosity is an appetite like hunger or thirst, but it is an appetite for understanding. As astronomy expands our horizons and we learn how distant stars and galaxies work, we feel satisfaction because we are learning about ourselves. We are beginning to understand what we are.

Study and Review

Summary

- ▶ Light is the visible form of **electromagnetic radiation (p. 99)**, an electric and magnetic disturbance that transports energy at the speed of light. The electromagnetic **spectrum (p. 100)** includes gamma rays, X-rays, ultraviolet radiation, visible light, infrared radiation, and radio waves.
- ▶ You can think of a particle of light, a **photon (p. 100)**, as a bundle of waves that sometimes acts as a particle and sometimes acts as a wave.
- ▶ The energy a photon carries depends on its **wavelength (p. 99)**. The wavelength of visible light, usually measured in **nanometers (p. 100)** (10^{-9} m) or **angstroms (p. 100)** (10^{-10} m), ranges from 400 nm to 700 nm (4000 to 7000 Å). Radio and **infrared radiation (p. 100)** have longer wavelengths and carry less energy. X-ray, gamma-ray, and **ultraviolet radiation (p. 100)** have shorter wavelengths and more energy.
- ▶ **Frequency (p. 99)** is the number of waves that pass a stationary point in 1 second. Wavelength equals the speed of light divided by the frequency.
- ▶ Earth's atmosphere is fully transparent in only two **atmospheric windows (p. 101)**—visible light and radio.
- ▶ Astronomical telescopes use a **primary lens (p. 101)** or **mirror (pp. 101–102)** (also called an **objective lens** or **mirror [pp. 101–102]**) to gather light and focus it into a small image, which can be magnified by an **eyepiece (p. 102)**. Short-**focal-length (p. 102)** lenses and mirrors must be more strongly curved and are more expensive to grind to shape.
- ▶ A **refracting telescope (p. 101)** uses a lens to bend the light and focus it into an image. Because of **chromatic aberration (p. 102)**, refracting telescopes cannot bring all colors to the same focus, resulting in color fringes around the images. An **achromatic lens (p. 102)** partially corrects for this, but such lenses are expensive and cannot be made much larger than about 1 m in diameter.
- ▶ **Reflecting telescopes (p. 101)** use a mirror to focus the light and are less expensive than refracting telescopes of the same diameter. Also, reflecting telescopes do not suffer from chromatic aberration. Most large telescopes are reflectors.
- ▶ **Light-gathering power (p. 103)** refers to the ability of a telescope to produce bright images. **Resolving power (p. 104)** refers to the ability of a telescope to resolve fine detail. **Diffraction fringes (p. 104)** in the image limit the detail visible. **Magnifying power (p. 105)**, the ability to make an object look bigger, is less important because it can be changed by changing the eyepiece.
- ▶ Astronomers build observatories on remote, high mountains for two reasons. Turbulence in Earth's atmosphere blurs the image of an astronomical telescope, a phenomenon that astronomers refer to as **seeing (p. 104)**. Atop a mountain, the air is steady, and the seeing is better. Observatories are located far from cities to avoid **light pollution (p. 106)**.
- ▶ In a reflecting telescope, light first comes to a focus at the **prime focus (p. 110)**, but **secondary mirrors (p. 110)** can direct light to other focus locations such as a **Cassegrain focus (p. 110)** or a **Newtonian focus (p. 110)**. The **Schmidt-Cassegrain focus (p. 110)** is popular for small telescopes.
- ▶ Because Earth rotates, telescopes must have a **sidereal drive (p. 111)** to follow the stars. An **equatorial mounting (p. 111)** with a **polar axis (p. 111)** makes this possible, but **alt-azimuth mountings (p. 111)** are becoming more popular.
- ▶ Very large telescopes can be built with **active optics (p. 111)**, maintaining the shape of floppy mirrors that are thin or in segments.

Such thin mirrors weigh less, are easier to support, and cool faster at nightfall.

- ▶ High-speed **adaptive optics (p. 109)** can monitor distortions caused by turbulence in Earth's atmosphere and partially cancel out the blurring caused by seeing.
- ▶ **Interferometry (p. 112)** refers to connecting two or more separate telescopes together to act as a single large telescope that has a resolution equivalent to that of a telescope as large in diameter as the separation between the telescopes.
- ▶ For many decades astronomers used photographic plates to record images at the telescope, but modern electronic systems such as **charge-coupled devices (CCDs) (p. 113)** have replaced photographic plates in most applications.
- ▶ Astronomical images in digital form can be computer enhanced and reproduced as **false-color images (p. 113)** to bring out subtle details.
- ▶ **Spectrographs (p. 113)** using prisms or a **grating (p. 113)** spread starlight out according to wavelength to form a spectrum revealing hundreds of **spectral lines (p. 113)** produced by atoms in the object being studied. A **comparison spectrum (p. 113)** containing lines of known wavelength allows astronomers to measure wavelengths in spectra of astronomical objects.
- ▶ Astronomers use radio telescopes for three reasons: They can detect cool hydrogen and other atoms and molecules in space; they can see through dust clouds that block visible light; and they can detect certain objects invisible at other wavelengths.
- ▶ Most radio telescopes contain a dish reflector, an antenna, an amplifier, and a data recorder. Such a telescope can record the intensity of the radio energy coming from a spot on the sky. Scans of small regions are used to produce radio maps.
- ▶ Because of the long wavelength, radio telescopes have very poor resolution, and astronomers often link separate radio telescopes together to form a **radio interferometer (p. 115)** capable of resolving much finer detail.
- ▶ Earth's atmosphere absorbs gamma rays, X-rays, ultraviolet, and far-infrared. To observe at these wavelengths, telescopes must be located in space.
- ▶ Earth's atmosphere distorts and blurs images. Telescopes in orbit are above this seeing distortion and are limited only by diffraction in their optics.
- ▶ **Cosmic rays (p. 119)** are not electromagnetic radiation; they are subatomic particles such as electrons and protons traveling at nearly the speed of light. They can best be studied from above Earth's atmosphere.

Review Questions

1. Why would you not plot sound waves in the electromagnetic spectrum?
2. If you had limited funds to build a large telescope, which type would you choose, a refractor or a reflector? Why?
3. Why do nocturnal animals usually have large pupils in their eyes? How is that related to astronomical telescopes?
4. Why do optical astronomers often put their telescopes at the tops of mountains, while radio astronomers sometimes put their telescopes in deep valleys?
5. Optical and radio astronomers both try to build large telescopes but for different reasons. How do these goals differ?
6. What are the advantages of making a telescope mirror thin? What problems does this cause?

- Small telescopes are often advertised as “200 power” or “magnifies 200 times.” As someone knowledgeable about astronomical telescopes, how would you improve such advertisements?
- Not too many years ago an astronomer said, “Some people think I should give up photographic plates.” Why might she change to something else?
- What purpose do the colors in a false-color image or false-color radio map serve?
- How is chromatic aberration related to a prism spectrograph?
- Why would radio astronomers build identical radio telescopes in many different places around the world?
- Why do radio telescopes have poor resolving power?
- Why must telescopes observing in the far-infrared be cooled to low temperatures?
- What might you detect with an X-ray telescope that you could not detect with an infrared telescope?
- The moon has no atmosphere at all. What advantages would you have if you built an observatory on the lunar surface?
- How Do We Know?** How is the resolution of an astronomical image related to the precision of a measurement?

Discussion Questions

- Why does the wavelength response of the human eye match so well the visual window of Earth’s atmosphere?
- Most people like beautiful sunsets with brightly glowing clouds, bright moonlit nights, and twinkling stars. Astronomers don’t. Why?

Problems

- The thickness of the plastic in plastic bags is about 0.001 mm. How many wavelengths of red light is this?
- What is the wavelength of radio waves transmitted by a radio station with a frequency of 100 million cycles per second?
- Compare the light-gathering powers of one of the 10-m Keck telescopes and a 0.5-m telescope.
- How does the light-gathering power of one of the Keck telescopes compare with that of the human eye? (*Hint:* Assume that the pupil of your eye can open to about 0.8 cm.)
- What is the resolving power of a 25-cm telescope? What do two stars 1.5 arc seconds apart look like through this telescope?
- Most of Galileo’s telescopes were only about 2 cm in diameter. Should he have been able to resolve the two stars mentioned in Problem 5?

- How does the resolving power of a 5-m telescope compare with that of the Hubble Space Telescope? Why does the HST outperform a 5-m telescope?
- If you build a telescope with a focal length of 1.3 m, what focal length should the eyepiece have to give a magnification of 100 times?
- Astronauts observing from a space station need a telescope with a light-gathering power 15,000 times that of the human eye, capable of resolving detail as small as 0.1 arc seconds and having a magnifying power of 250. Design a telescope to meet their needs. Could you test your design by observing stars from Earth?
- A spy satellite orbiting 400 km above Earth is supposedly capable of counting individual people in a crowd. Roughly what minimum-diameter telescope must the satellite carry? (*Hint:* Use the small-angle formula.)

Learning to Look

- The two images at the right show a star before and after an adaptive optics system was switched on. What causes the distortion in the first image, and how does adaptive optics correct the image?



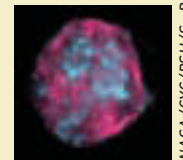
ESO

- The star images in the photo at the right are tiny disks, but the diameter of these disks is not related to the diameter of the stars. Explain why the telescope can’t resolve the diameter of the stars.



NASA, ESA and G. Meylan

- The X-ray image at right shows the remains of an exploded star. Explain why images recorded by telescopes in space are often displayed in false color rather than in the “colors” received by the telescope.



NASA/CXC/PSU/S. Park

7

Atoms and Starlight



Guidepost

In the last chapter, you read how telescopes gather starlight and how spectrographs spread out the light into spectra. Now you are ready to see what all the fuss is about. Here you will find answers to four essential questions:

— **What is an atom?**

— **How do atoms interact with light?**

— **What kinds of spectra do you see when you look at celestial objects?**

— **What can you learn from a star's spectrum?**

This chapter marks a change in the way you will look at nature. Up to this point, you have been thinking about what you can see with your eyes alone or aided by telescopes. In this chapter, you will begin using modern astrophysics to search out secrets that lie beyond what you can see.

The analysis of spectra is a powerful technique, and in the chapters that follow, you will use spectra to study stars, galaxies, and planets.

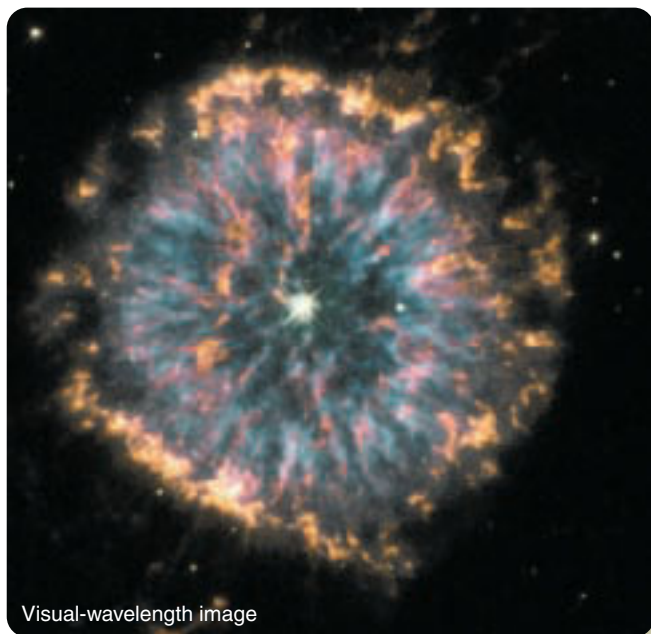
Clouds of gas 170,000 light-years away glow in this false-color image. Red represents sulfur atoms, green hydrogen, and blue oxygen. Clues hidden in the starlight tell a story of star birth and star death. (NASA, ESA, and M. Livio, STScI)

*Awake! for Morning in the Bowl of Night
Has flung the Stone that puts the Stars to
Flight:
And Lo! the Hunter of the East has caught
The Sultan's Turret in a Noose of Light.*

— THE RUBÁIYÁT OF OMAR KHAYYÁM, TRANS. EDWARD FITZGERALD

THE UNIVERSE IS FILLED with fabulously beautiful clouds of glowing gas illuminated by brilliant stars, but they are all hopelessly beyond reach. No laboratory jar on Earth holds a sample labeled “star stuff,” and no space probe has ever visited the inside of a star. The stars are far away, and the only information you can obtain about them comes hidden in starlight (■ Figure 7-1).

Earthbound humans knew almost nothing about stars until the early 19th century, when the German optician Joseph von Fraunhofer studied the solar spectrum and found it interrupted by some 600 dark lines representing colors that are missing from the sunlight Earth receives. When scientists realized that those spectral lines are related to the presence of various atoms in the



Visual-wavelength image

■ Figure 7-1

What’s going on here? The sky is filled with beautiful and mysterious objects that lie far beyond your reach—in the case of the nebula NGC 6751, about 6500 ly beyond your reach. The only way to understand such objects is by analyzing their light. Such an analysis reveals that this object is a dying star surrounded by the expanding shell of gas it ejected a few thousand years ago. You will learn more about this phenomenon in a later chapter. (NASA Hubble Heritage Team/STScI/AURA)

sun’s atmosphere, and found that the spectra of other stars have similar patterns of lines, a window finally opened to a scientific understanding of the sun and stars. In this chapter you will look through that window, seeing how the sun and other stars produce light, and how atoms interact with light to cause spectral lines. Once you understand that, you will know how astronomers determine the chemical composition of stars, as well as measure motions of gas at their surfaces and in their atmospheres.

7-1 Atoms

STARS ARE GREAT BALLS OF HOT GAS, and the atoms in that gas leave their marks on the light the stars emit. By understanding what atoms are and how they interact with light, you can decode the spectra of the stars and learn their secrets.

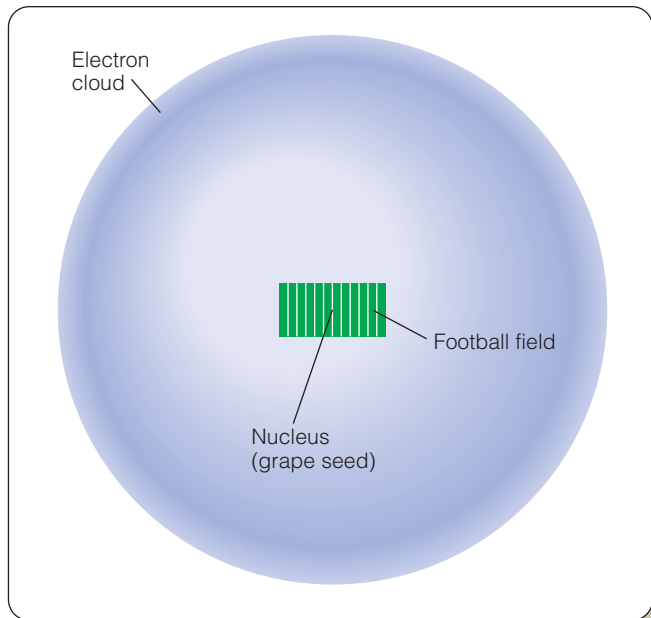
A Model Atom

To think about atoms and how they interact with light, you need a working model of an atom. In Chapter 2, you used a model of the sky, the celestial sphere. In this chapter, you will begin your study of atoms by creating a model of an atom. Remember that a model can have practical value without being true. The stars are not actually attached to a sphere surrounding Earth, but to navigate a ship or point a telescope, it is useful to pretend they are. The electrons in an atom are not actually little beads orbiting the nucleus the way planets orbit the sun, but for some purposes it is useful to picture them as such.

Your model atom contains a positively charged **nucleus** at the center, which consists of two kinds of particles: **Protons** carry a positive electrical charge, and **neutrons** have no charge. This means the nucleus has a net positive charge.

The nucleus of this model atom is surrounded by a cloud of orbiting **electrons**, low-mass particles with negative charges. Normally the number of electrons equals the number of protons, and the positive and negative charges balance to produce a neutral atom. Protons and neutrons have masses about 1840 times greater than that of an electron, so most of the mass of an atom lies in the nucleus. Even so, a single atom is not a massive object. A hydrogen atom, for example, has a mass of only 1.67×10^{-27} kg, about a trillionth of a trillionth of a gram.

An atom is mostly empty space. To see this, imagine constructing a simple scale model of a hydrogen atom. Its nucleus is a single proton with a diameter of about 0.0000016 nm, or 1.6×10^{-15} m. If you multiply this by one trillion (10^{12}), you can represent the nucleus of your model atom with something about 0.16 cm in diameter—a grape seed would do. The region of a hydrogen atom that contains the electron has a diameter of about 0.4 nm, or 4×10^{-10} m. Multiplying by a trillion increases the diameter to about 400 m, or about 4.5 football fields laid end to end (■ Figure 7-2). When you imagine a grape seed in the middle



■ **Figure 7-2**

Magnifying a hydrogen atom by 10^{12} makes the nucleus the size of a grape seed and the diameter of the electron cloud about 4.5 times larger than a football field.

of a sphere 4.5 football fields in diameter, you can see that an atom is mostly empty space.

Now you can consider a **Common Misconception**. Most people, without thinking about it much, imagine that matter is solid, but you have seen that atoms are mostly empty space. The chair you sit on, the floor you walk on, are mostly not there. When you study the deaths of stars in a later chapter, you will see what happens to a star when most of the empty space gets squeezed out of its atoms.

Different Kinds of Atoms

There are over a hundred chemical elements. The number of protons in the nucleus of an atom identifies which element it is. For example, a carbon atom has six protons in its nucleus. An atom with one more proton than this is nitrogen, and an atom with one fewer proton is boron.

Although an atom of a given element always has the same number of protons in its nucleus, the number of neutrons is less restricted. For instance, if you added a neutron to a carbon nucleus, it would still be carbon, but it would be slightly heavier. Atoms that have the same number of protons but a different number of neutrons are **isotopes**. Carbon has two stable isotopes. One contains six protons and six neutrons for a total of 12 particles and is thus called carbon-12. Carbon-13 has six protons and seven neutrons in its nucleus.

The number of electrons in an atom of a given element can vary. Protons and neutrons are bound tightly into the nucleus, but the electrons are held loosely in the electron cloud. Running

a comb through your hair creates a static charge by removing a few electrons from their atoms. An atom that has lost or gained one or more electrons is said to be **ionized** and is called an **ion**. A neutral carbon atom has six electrons that balance the positive charge of the six protons in its nucleus. If you ionize the atom by removing one or more electrons, the atom is left with a net positive charge. Under some circumstances, an atom may capture one or more extra electrons, giving it more negative charges than positive. Such a negatively charged atom is also considered an ion.

Atoms that collide may form bonds with each other by exchanging or sharing electrons. Two or more atoms bonded together form a **molecule**. Atoms do collide in stars, but the high temperatures cause violent collisions that are unfavorable for chemical bonding. Only in the coolest stars are the collisions gentle enough to permit the formation of chemical bonds. You will see later that the presence of molecules such as titanium oxide (TiO) in a star is a clue that the star is very cool. In later chapters, you will see that molecules also can form in cool gas clouds in space and in the atmospheres of planets.

Electron Shells

So far you have been thinking of the cloud of the whirling electrons in a general way, but now it is time to be more specific about how the electrons behave within the cloud.

Electrons are bound to the atom by the attraction between their negative charge and the positive charge on the nucleus. This attraction is known as the **Coulomb force**, after the French physicist Charles-Augustin de Coulomb (1736–1806). To ionize an atom, you need a certain amount of energy to pull an electron completely away from the nucleus. This energy is the electron's **binding energy**, the energy that holds it to the atom.

The size of an electron's orbit is related to the energy that binds it to the atom. If an electron orbits close to the nucleus, it is tightly bound, and a large amount of energy is needed to pull it away. Consequently, its binding energy is large. An electron orbiting farther from the nucleus is held more loosely, and less energy is needed to pull it away. That means it has less binding energy.

Nature permits atoms only certain amounts (quanta) of binding energy, and the laws that describe how atoms behave are called the laws of **quantum mechanics** (**How Do We Know? 7-1**). Much of this discussion of atoms is based on the laws of quantum mechanics.

Because atoms can have only certain amounts of binding energy, your model atom can have orbits only of certain sizes, called **permitted orbits**. These are like steps in a staircase: You can stand on the number-one step or the number-two step, but not on the number-one-and-one-quarter step—there isn't one. The electron can occupy any permitted orbit, but there are no orbits in between.

Quantum Mechanics

How can you understand nature if it depends on the atomic world you cannot see? You can see objects such as stars, planets, aircraft carriers, and hummingbirds, but you can't see individual atoms. As scientists apply the principle of cause and effect, they study the natural effects they can see and work backward to find the causes. Invariably that quest for causes leads back to the invisible world of atoms.

Quantum mechanics is the set of rules that describe how atoms and subatomic particles behave. On the atomic scale, particles behave in ways that seem unfamiliar. One of the principles of quantum mechanics specifies that you cannot know simultaneously the exact location and motion of a particle. This is why physicists prefer to go one step beyond the simple atomic model that has electrons following orbits and instead describe the electrons

in an atom as if they were a cloud of negative charge. That's a better model.

This raises some serious questions about reality. Is an electron really a particle at all? If you can't know simultaneously the position and motion of a specific particle, how can you know how it will react to a collision with a photon or another particle? The answer is that you can't know, and that seems to violate the principle of cause and effect.

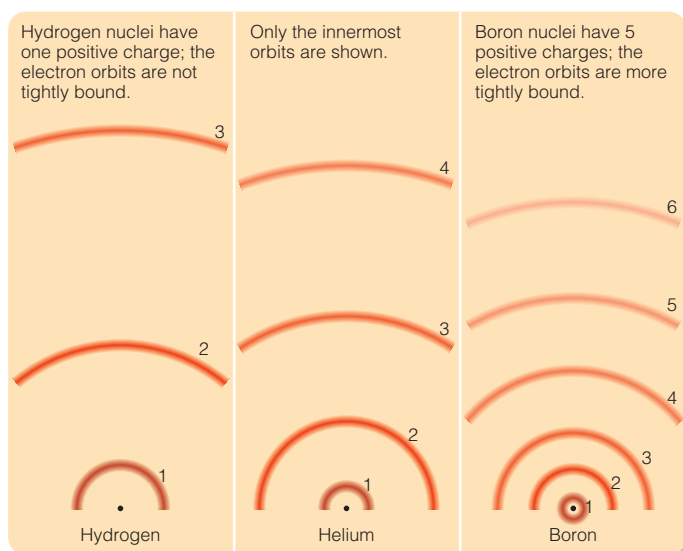
Many of the phenomena you can see depend on the behavior of huge numbers of atoms, and quantum mechanical uncertainties average out. Nevertheless, the ultimate causes that scientists seek lie at the level of atoms, and modern physicists are trying to understand the nature of the particles that make up atoms. That is one of the most exciting frontiers of science.



The world you see, including these neon signs, is animated by the properties of atoms and subatomic particles. (Jeff Greenberg/PhotoEdit)

The arrangement of permitted orbits depends primarily on the charge of the nucleus, which in turn depends on the number of protons. Consequently, each kind of element has its own pattern of permitted orbits (■ Figure 7-3). Isotopes of the same

elements have nearly the same pattern because they have the same number of protons. However, ionized atoms have orbital patterns that differ from their un-ionized forms. Thus, the arrangement of permitted orbits differs for every kind of atom and ion.



■ **Figure 7-3**

The electron in an atom may occupy only certain permitted orbits. Because different elements have different charges on their nuclei, the elements have different, unique patterns of permitted orbits.

SCIENTIFIC ARGUMENT

How many hydrogen atoms would it take to cross the head of a pin?

This is not a frivolous question. In answering it, you will discover how small atoms really are, and you will see how powerful physics and mathematics can be as a way to understand nature. Many scientific arguments are convincing because they have the precision of mathematics. To begin, assume that the head of a pin is about 1 mm in diameter. That is 0.001 m. The size of a hydrogen atom is represented by the diameter of the electron cloud, roughly 0.4 nm. Because 1 nm equals 10^{-9} m, you can multiply and discover that 0.4 nm equals 4×10^{-10} m. To find out how many atoms would stretch 0.001 m, you can divide the diameter of the pinhead by the diameter of an atom. That is, divide 0.001 m by 4×10^{-10} m, and you get 2.5×10^6 . It would take 2.5 million hydrogen atoms lined up side by side to cross the head of a pin.

Now you can see how tiny an atom is and also how powerful a bit of physics and mathematics can be. It reveals a view of nature beyond the capability of your eyes. Now build an argument using another bit of arithmetic. **How many hydrogen atoms would you need to add up to the mass of a paper clip (1 g)?**

7-2 The Interaction of Light and Matter

IF LIGHT DID NOT INTERACT WITH MATTER, you would not be able to see these words. In fact, you would not exist, because, among other problems, photosynthesis would be impossible, so there would be no grass, wheat, bread, beef, cheeseburgers, or any other kind of food. The interaction of light and matter makes life possible, and it also makes it possible for you to understand the universe.

You have already been considering a model hydrogen atom. Now you can use that model as you begin your study of light and matter. Hydrogen is both simple and common. Roughly 90 percent of all atoms in the universe are hydrogen.

The Excitation of Atoms

Each electron orbit in an atom represents a specific amount of binding energy, so physicists commonly refer to the orbits as **energy levels**. Using this terminology, you can say that an electron in its smallest and most tightly bound orbit is in its lowest permitted energy level, which is called the atom's **ground state**. You could move the electron from one energy level to another by supplying enough energy to make up the difference between the two energy levels. It would be like moving a flowerpot from a low shelf to a high shelf; the greater the distance between the shelves, the more energy you would need to raise the pot. The amount of energy needed to move the electron is the energy difference between the two energy levels.

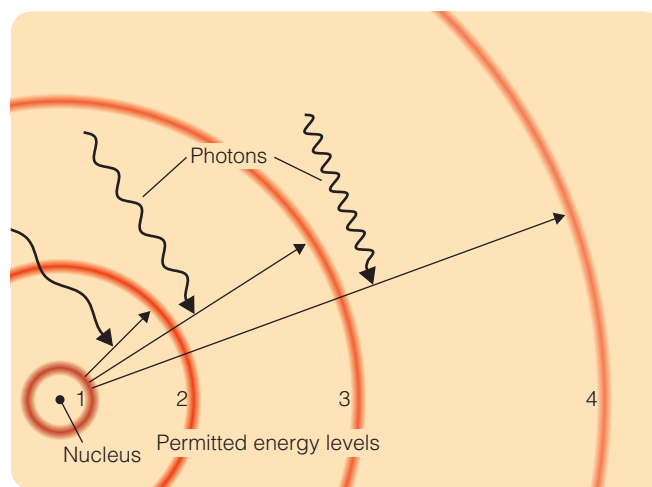
If you move an electron from a low energy level to a higher energy level, the atom becomes an **excited atom**. That is, you have added energy to the atom by moving its electron outward from the nucleus. An atom can become excited by collision. If two atoms collide, one or both may have electrons knocked into a higher energy level. This happens very commonly in hot gas, where atoms move rapidly and collide often.

Another way an atom can become excited is to absorb a photon. As you learned in the previous chapter, a photon is a bundle of electromagnetic waves with a specific energy. Only a photon with exactly the right amount of energy can move the electron from one level to another. If the photon has too much or too little energy, the atom cannot absorb it. Because the energy of a photon depends on its wavelength, only photons of certain wavelengths

can be absorbed by a given kind of atom. ■ Figure 7-4 shows the lowest four energy levels of the hydrogen atom, along with three photons the atom could absorb. The longest-wavelength photon has only enough energy to excite the electron to the second energy level, but the shorter-wavelength photons can excite the electron to higher levels. Because the hydrogen atom has many more energy levels than shown in Figure 7-4, it can absorb photons of many different wavelengths.

Atoms, like humans, cannot exist in an excited state forever. An excited atom is unstable and must eventually (usually within 10^{-6} to 10^{-9} second) give up the energy it has absorbed and return its electron to a lower energy level. Thus the electron in an excited atom tends to tumble down to its lowest energy level, its ground state.

When an electron drops from a higher to a lower energy level, it moves from a loosely bound level to one that is more tightly bound. The atom then has a surplus of energy—the energy difference between the levels—that it can emit as a photon with a wavelength corresponding to that amount of energy (Chapter 6). Study the sequence of events shown in ■ Figure 7-5 to see how an atom can absorb and emit photons. Because each type of atom or ion has a unique set of energy levels, each type absorbs and

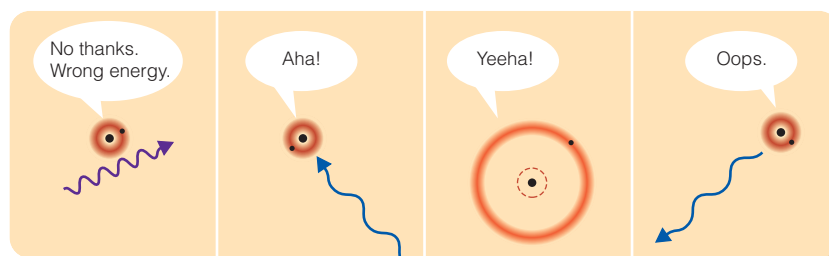


■ **Figure 7-4**

A hydrogen atom can absorb only those photons that move the atom's electron to one of the higher-energy orbits. Here three different photons are shown along with the change they would produce if they were absorbed.

■ **Figure 7-5**

An atom can absorb a photon only if the photon has the correct amount of energy. The excited atom is unstable and within a fraction of a second returns to a lower energy level, re-radiating the photon in a random direction.



emits photons with a unique set of wavelengths. As a result, you can identify the elements in a gas by studying the characteristic wavelengths of light that are absorbed or emitted.

The process of excitation and emission is a common sight in urban areas at night. A neon sign glows when atoms of neon gas in a glass tube are excited by electricity flowing through the tube. As the electrons in the electric current flow through the gas, they collide with the neon atoms and excite them. Almost immediately after a neon atom is excited, its electron drops back to a lower energy level, emitting the surplus energy as a photon of a certain wavelength. The photons emitted by excited neon blend to produce a reddish-orange glow. Signs of other colors, generically called “neon signs,” contain other gases or mixtures of gases instead of pure neon. Whenever you look at a neon sign, you are seeing atoms absorbing and emitting energy in the form of photons with specific colors determined by the structure of electron orbits in those atoms.

Neon signs are simple, but stars are complex. The colors of stars are not determined by the gases they contain. In the next section, you will discover why some stars are red and some are blue, and that will give you a new insight into how light interacts with matter.

Radiation from a Heated Object

If you look closely at the stars in the constellation Orion, you will notice that they are not all the same color (see Figure 2-4). One of your Favorite Stars, Betelgeuse, in the upper left corner of Orion, is quite red; another Favorite Star, Rigel, in the lower right corner, is blue. These differences in color arise from differences in temperature.

The starlight that you see comes from gases that make up the visible surface of the star, its photosphere. (Recall that you met the photosphere of the sun in Chapter 3.) Layers of gas deeper inside the star also emit light, but that light is reabsorbed before it can reach the surface. The gas above the photosphere is too thin to emit much light. The photosphere is the visible surface of a star because it is dense enough to emit lots of light but transparent enough to allow that light to escape.

Stars produce their light for the same reason heated horseshoes glow in a blacksmith’s forge—because they are hot. If a horseshoe is not too hot, it glows ruddy red, but as it heats up it grows brighter and yellower. Yellow-hot is hotter than red-hot but not as hot as white-hot.

The light from stars and from glowing horseshoes is produced by the acceleration of charged particles. Usually the accelerated particles are electrons because they are the least massive charged particles, and they are on the outsides of atoms, so they are the easiest to get moving. An electron is surrounded by an electric field; and, if you disturb an electron, the change in its electric field spreads outward at the speed of light as electromagnetic radiation. You learned in Chapter 5 that “acceleration” means any change in motion. Whenever you change the motion

of an electron or other charged particle, you generate electromagnetic waves. If you run a comb through your hair, you disturb electrons in both hair and comb, producing static electricity. That produces electromagnetic radiation, which you can hear as snaps and crackles if you are standing near an AM radio. Stars don’t comb their hair, of course, but they are hot, and they are made up of ionized gases, so there are plenty of electrons zipping around.

The molecules and atoms in any object are in constant motion, and in a hot object they are more agitated than in a cool object. You can refer to this agitation as **thermal energy**. If you touch an object that contains lots of thermal energy, it will feel hot as the thermal energy flows into your fingers. The flow of thermal energy is called **heat**. In contrast, **temperature** refers to the average speed of the particles. Hot cheese and hot green beans can have the same temperature, but the cheese can contain more thermal energy and can burn your tongue. Thus, *heat* refers to the flow of thermal energy, and *temperature* refers to the intensity of the agitation among the particles (**Focus on Fundamentals 3**).

When astronomers refer to the temperature of a star, they are talking about the temperature of the gases in the photosphere, and they express those temperatures on the **Kelvin temperature scale**. On this scale, zero degrees Kelvin (written 0 K) is **absolute zero** (−459.7°F), the temperature at which an object contains no thermal energy that can be extracted. Water freezes at 273 K and boils at 373 K. The Kelvin temperature scale is useful in astronomy because it is based on absolute zero and consequently is related directly to the motion of the particles in an object.

Now you can understand why a hot object glows, or to put it another way, why a hot object emits photon bundles of electromagnetic energy. The hotter an object is, the more motion there is among its particles. The agitated particles, including electrons, collide with each other, and when electrons accelerate—change their motion—part of the energy is carried away as electromagnetic radiation. The radiation emitted by a heated object is called **blackbody radiation**, a name translated from a German term that refers to the way a perfectly opaque object would behave. A perfectly opaque object would be both a perfect emitter and a perfect absorber of radiation. At room temperature, such a perfect absorber and emitter would look black, but at higher temperatures it would glow at wavelengths visible to a human eye. In astronomy and physics you will see the term *blackbody* referring to objects that glow brightly.

Blackbody radiation is quite common. In fact, it is responsible for the light emitted by an incandescent light bulb. Electricity flowing through the filament of the bulb heats it to high temperature, and it glows. You can also recognize the light emitted by a heated horseshoe as blackbody radiation. Many objects in the sky, including the sun and stars, primarily emit blackbody radiation because they are mostly opaque.

Temperature, Heat, and Thermal Energy

One of the most **Common Misconceptions** in science involves temperature. People often say “temperature” when they really mean “heat,” and sometimes they say “heat” when they mean something entirely different. This is a fundamental idea, so you need to understand the difference.

Even in an object that is solid, the atoms and molecules are continuously jiggling around bumping into each other. When something is hot, the particles are moving rapidly. Temperature is a measure of the average motion of the particles. (Mathematically, temperature is proportional to the square of the average velocity.) If you have your temperature taken, it will probably be 37.0°C (98.6°F), an indication that the atoms and molecules in your body are moving about at a normal pace. If you measure the temperature of a baby, the thermometer should register the same temperature, showing that the atoms and molecules in the baby’s body are moving at

the same average velocity as the atoms and molecules in your body.

The total energy of all of the moving particles in a body is called thermal energy. You have much more mass than the baby, so you must contain more thermal energy even though you have the same temperature. The thermal energy in your body and in the baby’s body has the same intensity (temperature) but different amounts. People often confuse temperature and thermal energy, so you must be careful to distinguish between them. Temperature is like an intensity, and thermal energy is a total amount.

Many people say “heat” when they should say “thermal energy.” Heat is the thermal energy that moves from a hot object to a cool object. If two objects have the same temperature, you and the infant for example, there is no transfer of thermal energy and no heat.

When you hear someone say “heat,” check to see if he or she doesn’t really mean thermal energy. You may have burned yourself on



What’s the difference between temperature and heat?

cheese pizza, but you probably haven’t burned yourself on green beans. At the same temperature, cheese holds more thermal energy than green beans. It isn’t the temperature that burns your tongue, but the flow of thermal energy, and that’s heat.

MASS | ENERGY | TEMPERATURE AND HEAT | DENSITY | PRESSURE

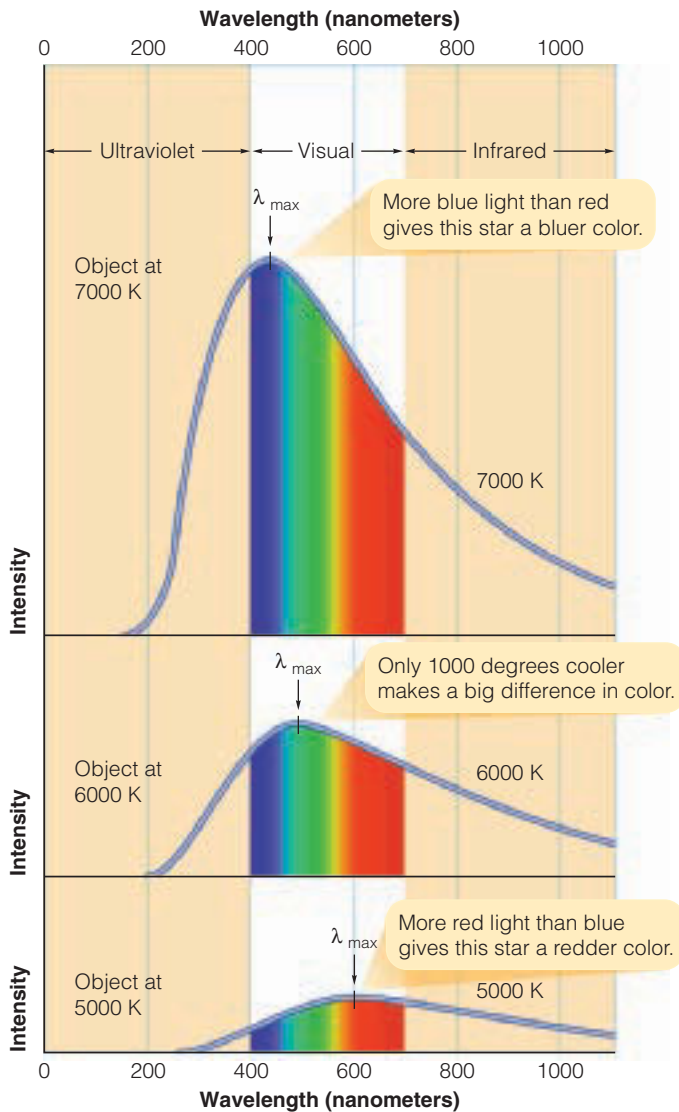
Hot objects emit blackbody radiation, but so do cold objects. Ice cubes are cold, but their temperature is higher than absolute zero, so they contain some thermal energy and must emit some blackbody radiation. The coldest gas drifting in space has a temperature only a few degrees above absolute zero, but it too emits blackbody radiation.

Two features of blackbody radiation are important. First, the hotter an object is, the more blackbody radiation it emits. Hot objects emit more radiation because their agitated particles collide more often and more violently with electrons. That’s why a glowing coal from a fire emits more total energy than an ice cube of the same size.

The second feature is the relationship between the temperature of the object and the wavelengths of the photons it emits. The wavelength of the photon emitted when a particle collides with an electron depends on the violence of the collision. Only a violent collision can produce a short-wavelength (high-energy) photon. The electrons in an object have a distribution of speeds; a few travel very fast, and a few travel very slowly, but most travel at intermediate speeds. The hotter the object is, the faster, on average, the electrons travel. Because high-velocity electrons are rare, extremely violent collisions don’t occur very often, and

short-wavelength photons are rare. Similarly, most collisions are not extremely gentle, so long-wavelength (low-energy) photons are also rare. Consequently, blackbody radiation is made up of photons with a distribution of wavelengths with medium wavelengths most common. The **wavelength of maximum intensity** (λ_{max}) is the wavelength at which the object emits the most intense radiation and occurs at some intermediate wavelength. (Make special note that λ_{max} does not refer to the maximum wavelength but to the wavelength of maximum.)

■ Figure 7-6 shows the intensity of radiation versus wavelength for three objects of different temperatures. The curves are high in the middle and low at either end because the objects emit most intensely at intermediate wavelengths. The total area under each curve is proportional to the total energy emitted, and you can see that the hotter object emits more total energy than the cooler objects. Look closely at the curves, and you will see that the wavelength of maximum intensity depends on temperature. The hotter an object, the shorter will be the wavelength of its maximum emitted intensity. The figure shows how temperature determines the color of a glowing blackbody. The hotter object emits more blue light than red and thus looks blue, and the cooler object emits more red than blue and consequently looks



■ **Figure 7-6**

Graphs of blackbody radiation intensity versus wavelength from three objects at different temperatures demonstrate that a hot body radiates more total energy and that the wavelength of maximum intensity is shorter for hotter objects. The hotter object here would look blue to your eyes, while the cooler object would look red.

red. Now you can understand why two of your Favorite Stars, Betelgeuse and Rigel, have such different colors. Betelgeuse is cool and looks red, but Rigel is hot and looks blue.

Cool objects don't glow at visible wavelengths but still produce blackbody radiation. For example, the human body has a temperature of 310 K and emits blackbody radiation mostly in the infrared part of the spectrum. Infrared security cameras can detect burglars by the radiation they emit, and mosquitoes can track you down in total darkness by homing in on your infrared radiation. Although you emit lots of infrared radiation, you rarely emit higher-energy photons; and you almost never emit an

X-ray or gamma-ray photon. Your wavelength of maximum intensity lies in the infrared part of the spectrum.

Two Radiation Laws

The two features of blackbody radiation that you have just considered can be given precise mathematical form, and they have proven so dependable that they are known as laws. One law is related to energy and one to color.

As you saw in the previous section, a hot object emits more blackbody radiation than a cool object. That is, it emits more energy. Recall from Chapter 5 that energy is expressed in units called joules (J); 1 joule is about the energy of an apple falling from a table to the floor. The total radiation given off by 1 square meter of the surface of the object in joules per second equals a constant number, represented by σ times the temperature raised to the fourth power.* This relationship is called the Stefan-Boltzmann law:

$$E = \sigma T^4 \text{ (J/s/m}^2\text{)}$$

How does this help you understand stars? Suppose a star the same size as the sun had a surface temperature that was twice as hot as the sun's surface. Then each square meter of that star would radiate not twice as much energy, but 2^4 , or 16, times as much energy. From this law you can see that a small difference in temperature can produce a very large difference in the amount of energy a star's surface emits.

The second radiation law is related to the color of stars. In the previous section, you saw that hot stars look blue and cool stars look red. Wien's law written for conventional intensity units tells you that the wavelength at which a star radiates the most energy, its wavelength of maximum intensity (λ_{max}), depends only on the star's temperature:

$$\lambda_{\text{max}} = 2.90 \times 10^6 / T$$

That is, the wavelength of maximum radiation in nanometers equals 2.9 million divided by the temperature on the Kelvin scale.

This law is a powerful tool in astronomy, because it relates the temperature of a star to its wavelength of maximum intensity. For example, you might find a star emitting light with a maximum intensity at a wavelength of 1000 nm—in the near-infrared. Then the surface temperature of the star must be 2900 K. Later you will meet stars much hotter than the sun; such stars radiate most of their energy at very short wavelengths. The hottest stars, for instance, radiate most of their energy in the ultraviolet.

*For the sake of completeness, you can note that the constant σ equals $5.67 \times 10^{-8} \text{ J/(s m}^2 \text{ K}^4\text{)}$ (units of joules per second per square meter per degree Kelvin to the fourth power).

SCIENTIFIC ARGUMENT

The infrared radiation coming out of your ear can tell a doctor your temperature. How does that work?

You know two radiation laws, so your argument must use the right one. Doctors and nurses use a handheld device to measure body temperature by observing the infrared radiation emerging from a patient's ear. You might suspect the device depends on the Stefan-Boltzmann law and measures the intensity of the infrared radiation. A person with a fever will emit more energy than a healthy person. However, a healthy person with a large ear canal would emit more than a person with a small ear canal, so measuring intensity would not be helpful. The device actually depends on Wien's law, finding temperature by measuring the "color" of the infrared radiation. A patient with a fever will emit at a slightly shorter wavelength of maximum intensity, and the infrared radiation emerging from his or her ear will be a tiny bit "bluer" than that emitted by a person with normal temperature.

Astronomers can measure the temperatures of stars the same way. Adapt your argument for stars. **Use Figure 7-6 to explain how the colors of stars reveal their temperatures.**

7-3 Stellar Spectra

SCIENCE IS A WAY OF UNDERSTANDING NATURE, and the spectrum of a star can tell you a great deal about the star's temperature, motion, and composition. In later chapters, you will use spectra to study many more astronomical objects such as galaxies and planets, but you can begin by looking at the spectra of stars, including that of the sun.

The Formation of a Spectrum

The spectrum of a star is formed as light passes outward through the gases near its surface. Read **Atomic Spectra** on pages 132–133 and notice that it describes three important properties of spectra and defines 12 new terms that will help you discuss astronomical spectra:

- 1 There are three kinds of spectra: (i) *continuous spectra*; (ii) *absorption* or *dark-line spectra*, which contain *absorption lines*; and (iii) *emission* or *bright-line spectra*, which contain *emission lines*. These spectra are described by *Kirchhoff's laws*. When you see one of these types of spectra, you can recognize the kind of matter that emitted the light.
- 2 Photons are emitted or absorbed when an electron in an atom makes a *transition* from one energy level to another. The wavelengths of the photons depend on the energy difference between the two levels. Hydrogen atoms can produce many spectral lines in series such as the *Lyman*, *Balmer*, and *Paschen* series. Only three lines in the Balmer series are visible to human eyes. The emitted photons coming from a hot cloud of hydrogen gas have the same

wavelengths as the photons absorbed by hydrogen atoms in the gases of a star.

- 3 Most modern astronomy books display spectra as graphs of intensity versus wavelength. Be sure you recognize the connection between the dark absorption lines and the dips in the graphed spectrum.

Whatever kind of celestial object's spectrum astronomers look at, the most common spectral lines are the Balmer lines of hydrogen. In the next section, you will see how Balmer lines can tell you the temperature of a star's surface.

The Balmer Thermometer

You can use the Balmer absorption lines as a thermometer to find the temperatures of stars. From the discussion of blackbody radiation, you already know how to estimate temperature using color, but the Balmer lines give you much greater accuracy.

Recall that astronomers use the Kelvin temperature scale when referring to stellar temperatures. These temperatures range from about 40,000 K to about 2500 K and refer to the temperature of the star's surface. Compare these extremes with the surface temperature of the sun, about 5800 K. The centers of stars are much hotter—millions of degrees—but the colors and spectra of stars tell you only about the surface because that's where the light comes from.

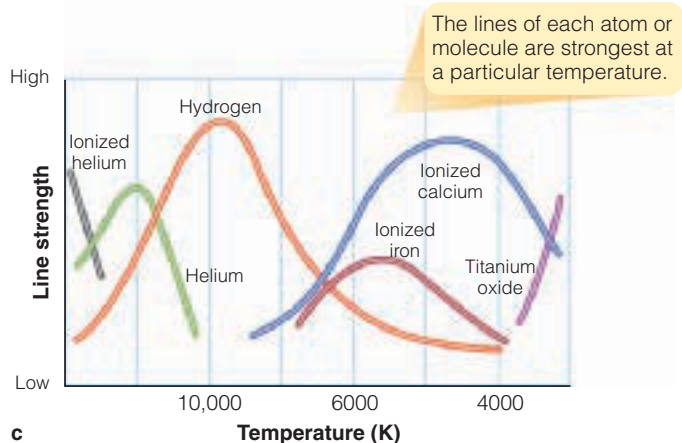
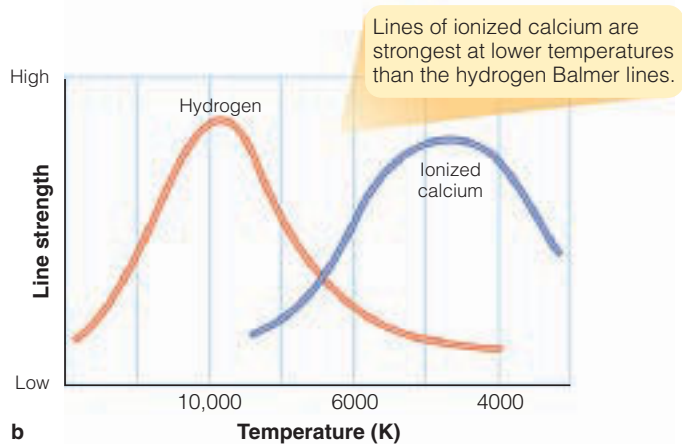
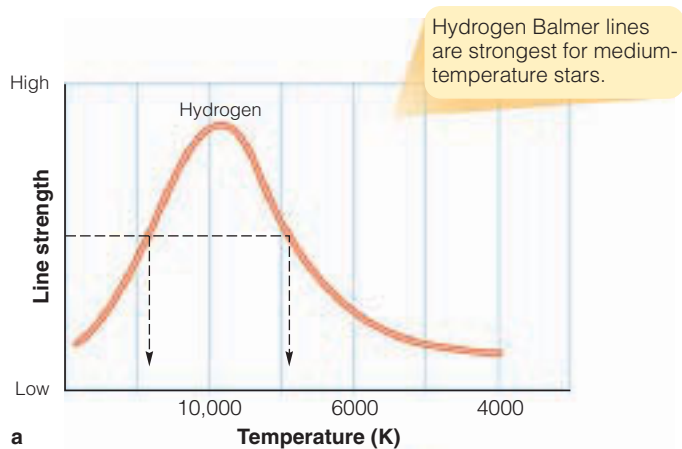
The Balmer thermometer works because the strength of the Balmer lines depends on the temperature of the star's surface layers. Both hot and cool stars have weak Balmer lines, but medium-temperature stars have strong Balmer lines.

The Balmer absorption lines are produced only by atoms with electrons in the second energy level. If a star is cool, there are few violent collisions between atoms to excite the electrons, so the electrons of most atoms are in the ground state, not the second level. Electrons in the ground state can't absorb photons in the Balmer series. As a result, you should expect to find weak Balmer absorption lines in the spectra of cool stars.

In the surface layers of hot stars, on the other hand, there are many violent collisions between atoms. These collisions can excite electrons to high energy levels or ionize some atoms by knocking electrons out of the atoms. Consequently, there are few hydrogen atoms with their electrons in the second orbit to form Balmer absorption lines. Hot stars, like cool stars, have weak Balmer absorption lines.

In stars of an intermediate temperature, roughly 10,000 K, the collisions are just right to excite large numbers of electrons into the second energy level. Hydrogen gas at that temperature absorbs Balmer wavelength photons very well and produces strong Balmer lines.

Theoretical calculations can predict exactly how strong the Balmer lines should be for stars of various temperatures. Such calculations are the key to finding temperatures from stellar



■ **Figure 7-7**

The strength of spectral lines can tell you the temperature of a star. (a) Balmer hydrogen lines alone are not enough because they give two answers. Balmer lines of a certain strength could be produced by a hotter star or a cooler star. (b) Adding another atom to the diagram helps, and (c) adding many atoms and molecules to the diagram creates a precise aid to find the temperatures of stars.

spectra. The curve in ■ Figure 7-7a shows the strength of the Balmer lines for various stellar temperatures. But you can see from the graph that a star with Balmer lines of a certain strength might have either of two temperatures, one high and one low. How do you know which is right? You must examine other spectral lines to choose the correct temperature.

Temperature has a similar effect on the spectral lines of other elements, but the temperature at which the lines reach their maximum strength differs for each element (Figure 7-7b). If you add a number of chemical elements to your graph, you will have a powerful aid for finding the stars' temperatures (Figure 7-7c).

Now you can determine a star's temperature by comparing the strengths of its spectral lines with your graph. For instance, if you found medium-strength Balmer lines and strong helium lines in a star's spectrum, you could conclude that it had a temperature of about 20,000 K. But if the star had weak hydrogen lines and strong lines of ionized iron, you would assign it a temperature of about 5800 K, similar to that of the sun.

The spectra of stars cooler than about 3500 K contain dark bands produced by molecules such as titanium oxide (TiO). Because of their structure, molecules can absorb photons at many wavelengths, producing numerous, closely spaced spectral lines that blend together to form bands. These molecular bands appear in the spectra of only the coolest stars because, as mentioned before, molecules in cool stars are not subject to the violent collisions that would break them apart in hotter stars.

Spectral Classification

You have seen that the strengths of a star's various spectral lines depend on its surface temperature. From this you can conclude that all stars of a given temperature should have similar spectra. If you learn to recognize the pattern of spectral lines produced by a 6000 K star, for instance, you need not use Figure 7-7c every time you see that kind of spectrum. You can save time by classifying stellar spectra rather than analyzing each one individually.

The first widely used classification system was devised by astronomers at Harvard during the 1890s and 1900s. One of the astronomers, Annie J. Cannon, personally inspected and classified the spectra of over 250,000 stars. The spectra were first classified into groups labeled A through Q, but some groups were later dropped, merged with others, or reordered. The final classification includes the seven major **spectral classes**, or **types**, still used today: O, B, A, F, G, K, M.*

This sequence of spectral types, called the **spectral sequence**, is important because it is a temperature sequence. The O stars are the hottest, and the temperature decreases along the sequence to the M stars, the coolest. For increased precision, astronomers divide each spectral class into ten subclasses. For example, spectral class A consists of the subclasses A0, A1, A2, . . . A8, A9. Next come F0, F1, F2, and so on. This finer division gives a star's temperature to an accuracy of about 5 percent. The sun, for example, is not just a

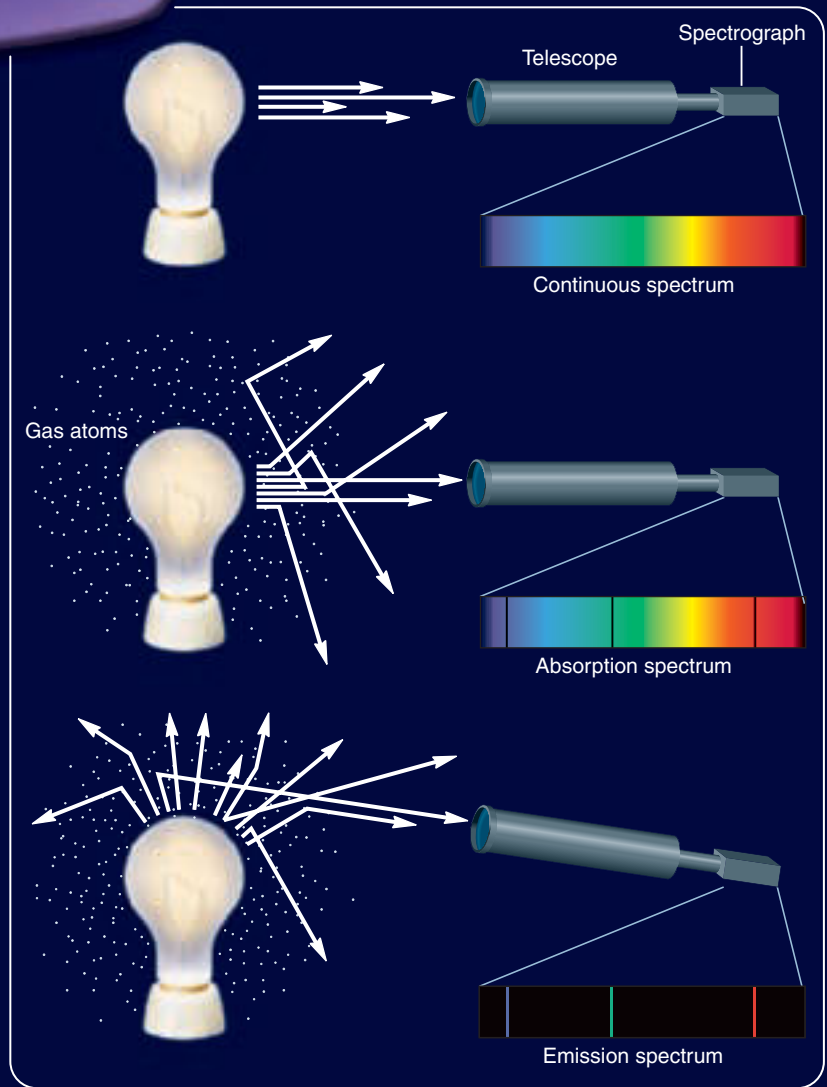
*Generations of astronomy students have remembered the spectral sequence using the mnemonic "Oh, Be A Fine Girl (Guy), Kiss Me." More recent suggestions from students include "Oh Boy, An F Grade Kills Me" and "Only Bad Astronomers Forget Generally Known Mnemonics."

Atomic Spectra

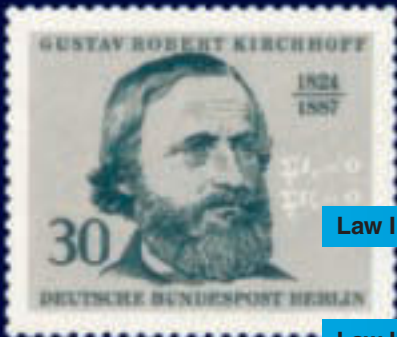
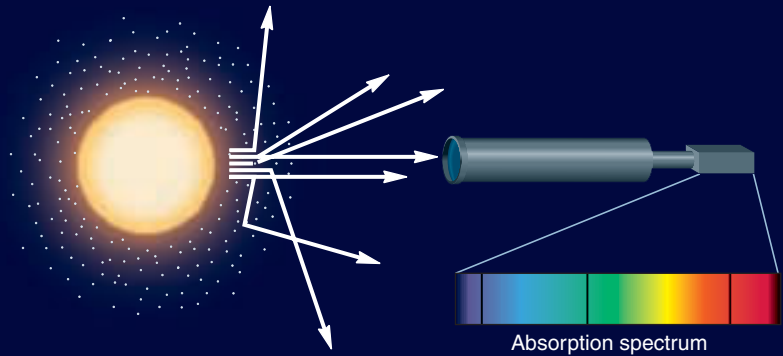
1 To understand how to analyze a spectrum, begin with a simple incandescent lightbulb. The hot filament emits blackbody radiation, which forms a **continuous spectrum**.

An **absorption spectrum** results when radiation passes through a cool gas. In this case you can imagine that the lightbulb is surrounded by a cool cloud of gas. Atoms in the gas absorb photons of certain wavelengths, which are missing from the spectrum, and you see their positions as dark **absorption lines**. Such spectra are sometimes called **dark-line spectra**.

An **emission spectrum** is produced by photons emitted by an excited gas. You could see **emission lines** by turning your telescope aside so that photons from the bright bulb did not enter the telescope. The photons you would see would be those emitted by the excited atoms near the bulb. Such spectra are also called **bright-line spectra**.



1a The spectrum of a star is an absorption spectrum. The denser layers of the photosphere emit blackbody radiation. Gases in the atmosphere of the star absorb their specific wavelengths and form dark absorption lines in the spectrum.



KIRCHHOFF'S LAWS

Law I: The Continuous Spectrum

A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a continuous spectrum.

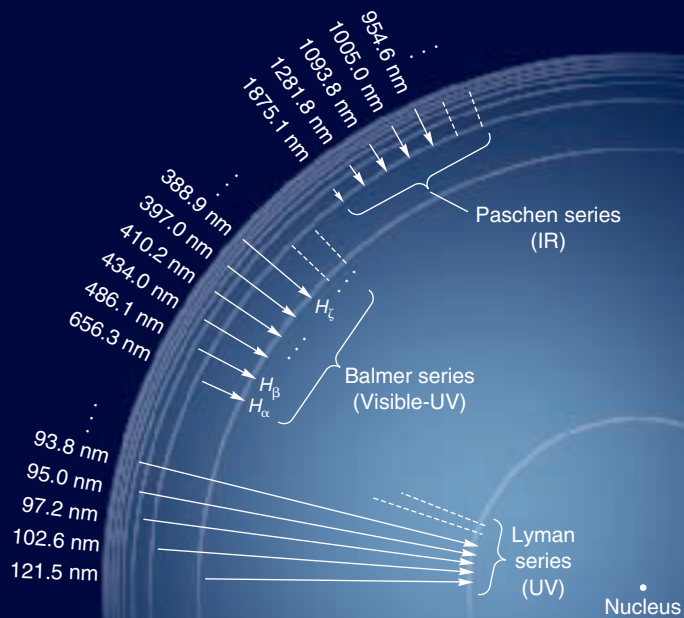
Law II: The Emission Spectrum

A low-density gas excited to emit light will do so at specific wavelengths and thus produce an emission spectrum.

Law III: The Absorption Spectrum

If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.

1b In 1859, long before scientists understood atoms and energy levels, the German scientist Gustav Kirchhoff formulated three rules, now known as **Kirchhoff's laws**, that describe the three types of spectra.



2 The electron orbits in the hydrogen atom are shown here as energy levels. When an electron makes a **transition** from one orbit to another, it changes the energy stored in the atom. In this diagram, arrows pointed inward represent transitions that result in the emission of a photon. If the arrows pointed outward, they would represent transitions that result from the absorption of a photon. Long arrows represent large amounts of energy and correspondingly short-wavelength photons.

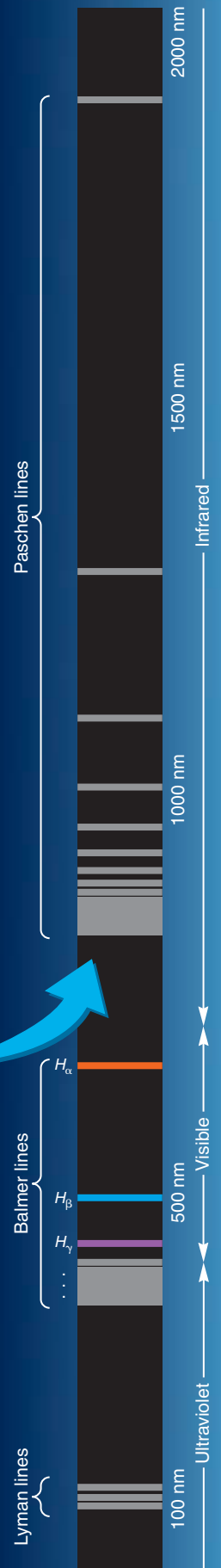
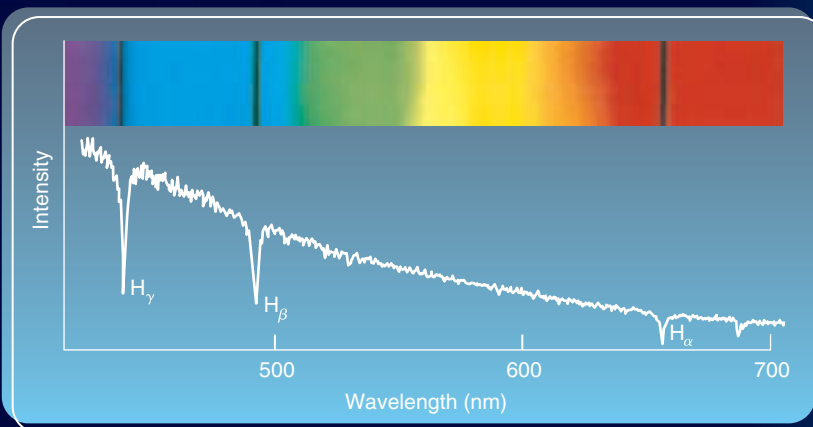
2a Transitions in the hydrogen atom can be grouped into series—the **Lyman series**, **Balmer series**, **Paschen series**, and the like. Transitions and the resulting spectral lines are identified by Greek letters. Only the first few transitions in the first three series are shown at left.

2b In this drawing (right) of the hydrogen spectrum, emission lines in the infrared and ultraviolet are shown as gray. Only the first three lines of the Balmer series are visible to human eyes.

2c Excited clouds of gas in space emit light at all of the Balmer wavelengths, but you see only the red, blue, and violet photons blending to create the pink color typical of ionized hydrogen.



3 Modern astronomers rarely work with spectra as bands of light. Spectra are usually recorded digitally, so it is easy to represent them as graphs of intensity versus wavelength. Here the artwork above the graph suggests the appearance of a stellar spectrum. The graph below reveals details not otherwise visible and allows comparison of relative intensities. Notice that dark absorption lines in the spectrum appear as dips in the curve of intensity.



The shorter-wavelength lines in each series blend together.

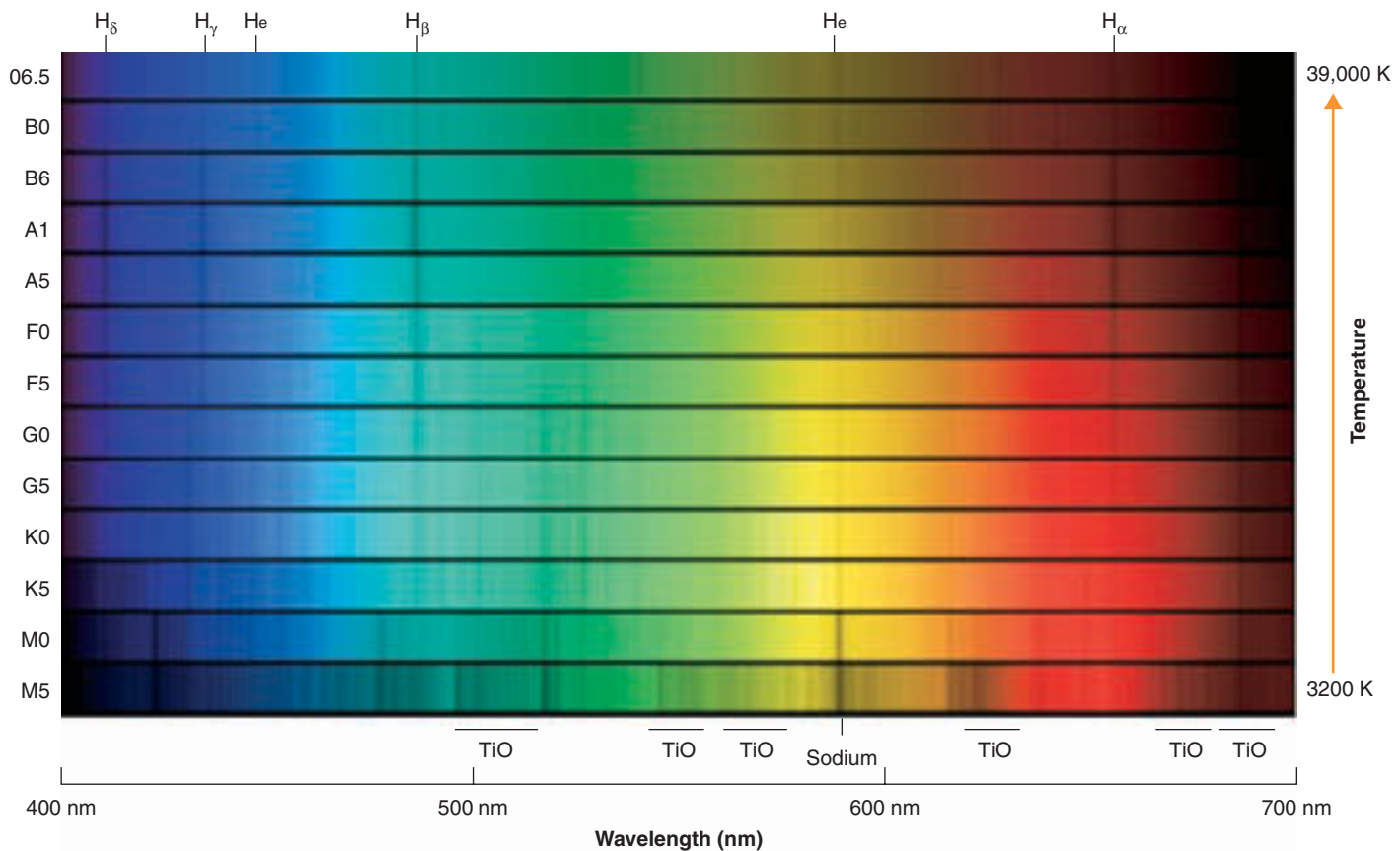
■ **Table 7-1 | Spectral Classes**

Spectral Class	Approximate Temperature (K)	Hydrogen Balmer Lines	Other Spectral Features	Naked-Eye Example
O	40,000	Weak	Ionized helium	Meissa (O8)
B	20,000	Medium	Neutral helium	Achernar (B3)
A	10,000	Strong	Ionized calcium weak	Sirius (A1)
F	7500	Medium	Ionized calcium weak	Canopus (F0)
G	5500	Weak	Ionized calcium medium	Sun (G2)
K	4500	Very weak	Ionized calcium strong	Arcturus (K2)
M	3000	Very weak	TiO strong	Betelgeuse (M2)

G star, but a G2 star. ■ Table 7-1 breaks down some of the information contained in Figure 7-7c and presents it in tabular form according to spectral class. For example, if a star has weak Balmer lines and lines of ionized helium, it must be an O star.

Thirteen stellar spectra are arranged in ■ Figure 7-8 from the hottest at the top to the coolest at the bottom. You can easily see how the strength of spectral lines depends on temperature.

The Balmer lines are strongest in A stars, where the temperature is moderate but still high enough to excite the electrons in hydrogen atoms to the second energy level, where they can absorb Balmer wavelength photons. In the hotter stars (O and B), the Balmer lines are weaker because the higher temperature excites the electrons to energy levels above the second or ionizes the atoms. The Balmer lines in cooler stars (F through M) are also



■ **Figure 7-8**

These spectra show stars ranging from hot O stars at the top to cool M stars at the bottom. The Balmer lines of hydrogen are strongest at spectral type A0, but the two closely spaced lines of sodium in the yellow are strongest for very cool stars. Helium lines appear only in the spectra of the hottest stars. Notice that the helium line visible in the top spectrum has nearly but not exactly the same wavelength as the sodium lines visible in cooler stars. Bands produced by the molecule titanium oxide are strong in the spectra of the coolest stars. (AURA/NOAO/NSF)

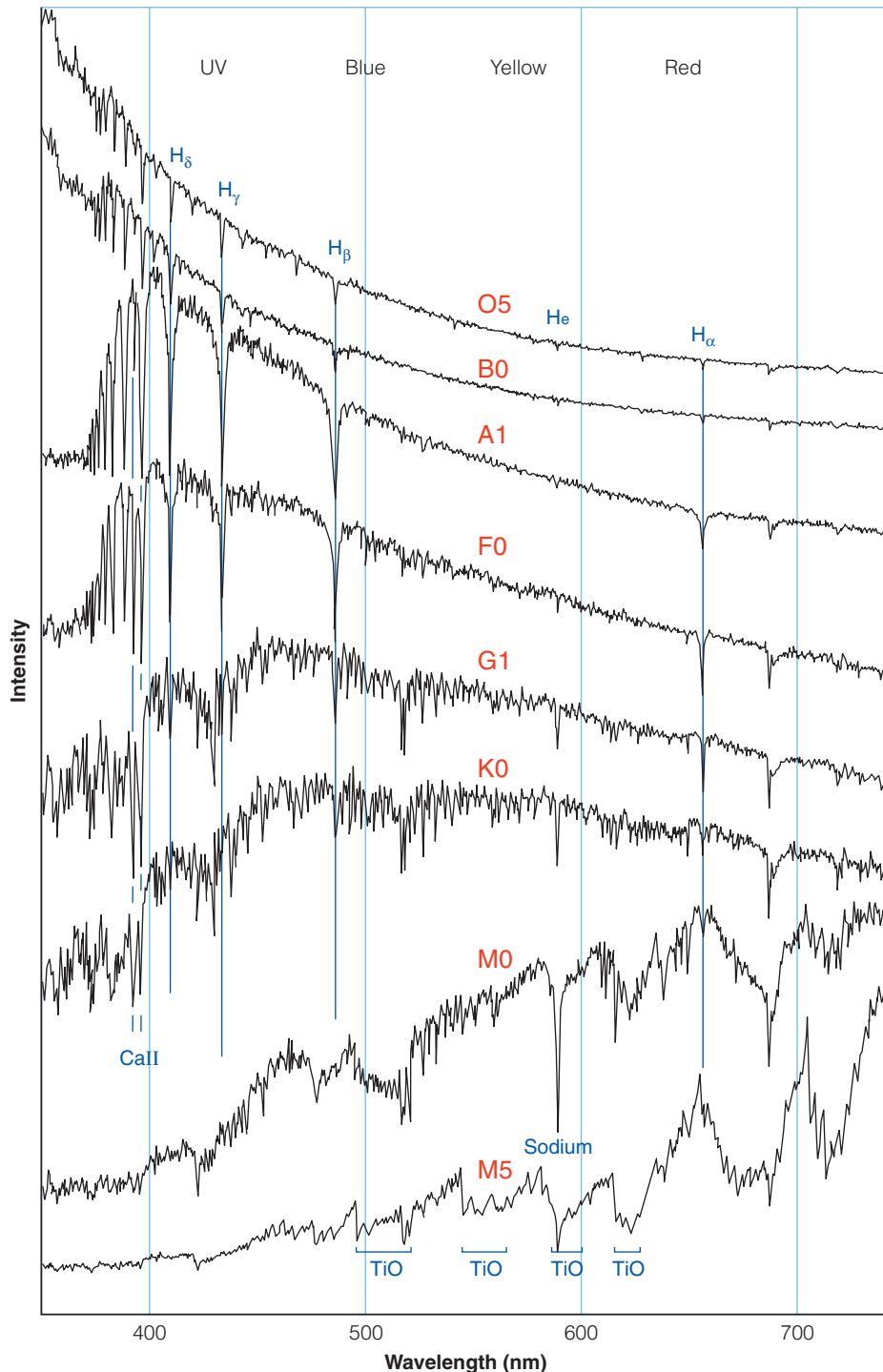
weaker but for a different reason. The lower temperature cannot excite many electrons to the second energy level, so few hydrogen atoms are capable of absorbing Balmer wavelength photons.

Although these spectra are attractive, astronomers rarely work with spectra as color images. Rather, they display spectra as graphs of intensity versus wavelength that show dark absorption lines as dips in the graph (■ Figure 7-9). Such graphs allow more detailed analysis than photographs. Notice, for example, that the overall curves are segments of blackbody curves with spectral

lines superimposed. The wavelength of maximum intensity is in the infrared for the coolest stars and in the ultraviolet for the hottest stars. Look carefully at these graphs, and you can see that helium is visible only in the spectra of the hottest classes and titanium oxide bands only in the coolest. Two lines of ionized calcium increase in strength from A to K and then decrease from K through M. Because the strengths of these spectral lines depend on temperature, it requires only a few moments to study a star's spectrum and determine its temperature.

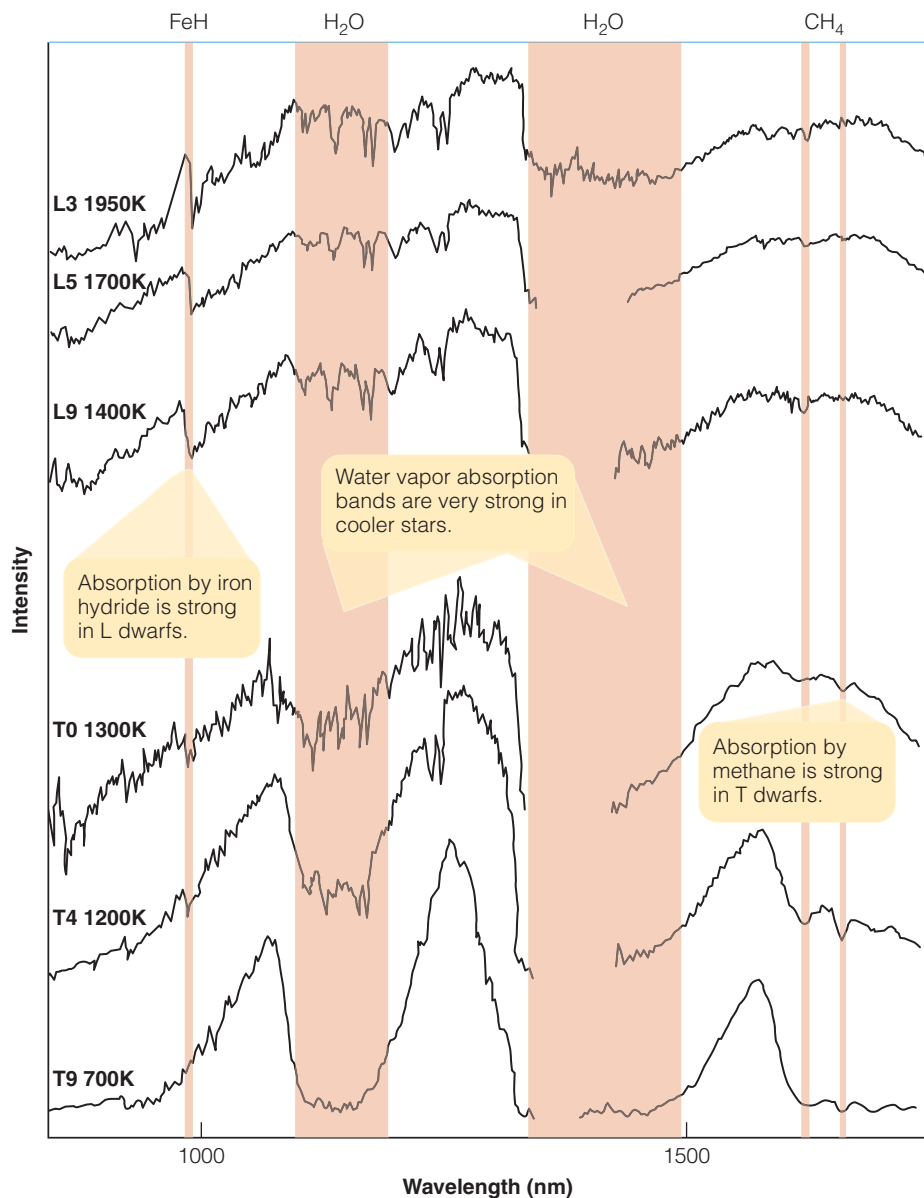
Now you can learn something new about your Favorite Stars. Sirius, brilliant in the winter sky, is an A1 star; and Vega, bright overhead in the summer sky, is an A0 star. They have nearly the same temperature and color, and both have strong Balmer lines in their spectra. The bright red star in Orion is Betelgeuse, a cool M2 star, but blue-white Rigel is a hot B8 star. Polaris, the North Star, is an F8 star a bit hotter than our sun, and Alpha Centauri, the closest star to the sun, is a G2 star just like the sun.

The study of spectral types is a century old, but astronomers continue to discover new types. The **L dwarfs**, found in 1998, are cooler and fainter than M stars, and are understood to be objects smaller than stars but larger than planets called “brown dwarfs” that you will learn about in a later chapter. The spectra of M stars contain bands produced by metal oxides such as titanium oxide (TiO), but L dwarf spectra contain bands produced by molecules such as iron hydride (FeH). The **T dwarfs**, discovered in 2000, are an even cooler and fainter type of brown dwarf than L dwarfs. Their spectra show absorption by methane (CH₄) and water vapor (■ Figure 7-10). The development of giant telescopes and highly sensitive infrared cameras and spectrographs is allowing astronomers to find and study these cool objects.



■ **Figure 7-9**

Modern digital spectra are often represented as graphs of intensity versus wavelength with dark absorption lines appearing as sharp dips in the curves. The hottest stars are at the top and the coolest at the bottom. Hydrogen Balmer lines are strongest at about A0, while lines of ionized calcium (Ca II) are strong in K stars. Titanium oxide (TiO) bands are strongest in the coolest stars. Compare these spectra with Figures 7-7c and 7-8. (Courtesy NOAO, G. Jacoby, D. Hunter, and C. Christian)



■ **Figure 7-10**

These six infrared spectra show the dramatic differences between L dwarfs and T dwarfs. Spectra of M stars show titanium oxide bands (TiO), but L and T dwarfs are so cool that TiO molecules do not form. Other molecules, such as iron hydride (FeH), water (H₂O), and methane (CH₄), can form in these very cool objects. (Adapted from Thomas R. Geballe, Gemini Observatory, from a graph that originally appeared in *Sky and Telescope Magazine*, February 2005, p. 37.)

The Composition of the Stars

It seems as though it should be easy to learn the composition of the sun and stars just by looking at their spectra, but this is actually a difficult problem that wasn't well understood until the 1920s. The story is worth telling, not only because it illustrates the temperature dependence of stellar spectral types, it is also the story of an important American astronomer who waited decades to get proper credit for her work.

As a child in England, Cecilia Payne (1900–1979) excelled in classics, languages, mathematics, and literature, but her first love was astronomy. After finishing Newnham College in Cambridge, she left England, sensing that there were few opportunities there for a woman in science. In 1922, Payne arrived at Harvard, where she eventually earned her Ph.D. (although her degree was awarded by Radcliffe because Harvard did not then admit women).

In her thesis, Payne attempted to relate the strength of the absorption lines in stellar spectra to the physical conditions in the atmospheres of the stars. This was not easy; a given spectral line can be weak because the atom is rare or because the temperature is either too high or too low for it to absorb efficiently. If you see sodium lines in a star's spectrum, you can be sure that the star contains sodium atoms, but if you see no sodium lines, you must consider the possibility that sodium is present but the star is too hot or too cool for that type of atom to produce detectable spectral lines.

Density is another factor. If a gas is dense, the atoms are packed tighter together, collide more often, distort the electron orbits, and thereby change the strength of spectral lines (**Focus on Fundamentals 4**). If the gas is low density, the atoms collide less often and the spectral lines are less affected.

Payne's problem was to untangle these factors and find both the true temperatures of the stars and the true abundance of the atoms in their atmospheres. Solving this puzzle required some of the most recent advances in

atomic physics and quantum mechanics. About the time Payne left Cambridge University, Indian physicist Meghnad Saha published his work on the ionization of atoms. Drawing from such theoretical work, Payne's calculations showed that over 90 percent of the atoms in stars (including the sun) must be hydrogen and most of the rest are helium (■ Table 7-2). The heavier atoms like calcium, sodium, and iron seem more abundant only because they are better at absorbing photons at the temperatures of stars.

At the time, astronomers found it hard to believe Payne's abundances of hydrogen and helium. They especially found such a high abundance of helium unacceptable. After all, hydrogen lines are at least visible in most stellar spectra, but helium lines are almost invisible in the spectra of all but the hottest stars. Nearly all astronomers assumed that the stars had roughly the same composition as Earth's surface; that is, they believed that the stars were composed mainly of heavier atoms such as carbon,

Density

You are about as dense as an average star. What does that mean? As you study astronomy, you will use the term *density* often, so you should be sure to understand this fundamental concept. **Density** is a measure of the amount of matter in a given volume. Density is expressed as mass per volume, such as grams per cubic centimeter. The density of water, for example, is about 1 g/cm^3 , and you are almost as dense as water.

To get a feel for density, imagine holding a brick in one hand and a similar-sized block of Styrofoam in the other hand. You can easily tell that the brick contains more matter than the Styrofoam block, even though both are the same size. The brick weighs more than the Styrofoam, but it isn't really the weight that you should consider. Rather, you should think about the mass of the two objects. In space, where they have no weight, the brick and the Styrofoam would still have mass, and

you could tell just by moving them around that the brick contains more mass than the Styrofoam. For example, imagine tapping each object gently with your hand. The massive brick would be easy to distinguish from the low-mass Styrofoam block, even in weightlessness.

Density is a fundamental concept in science because it is a general property of materials. Metals tend to be dense; lead, for example, has a density of about 7 g/cm^3 . Rock, in contrast, has a density of 3 to 4 g/cm^3 . Water and ice have densities of about 1 g/cm^3 . If you knew that a small moon orbiting Saturn had a density of 1.5 g/cm^3 , you could immediately draw some conclusions about what kinds of materials the little moon might be made of—ice and a little rock, but not much metal. The density of an object is a basic clue to its composition.

Astronomical bodies can have dramatically different densities. The gas clouds between



A brick would be dense even in space where it had no weight.

the stars can have very low densities, but the same kind of gas in a star can have a much higher density. The sun, for example, has an average density of about 1 g/cm^3 , about the same as your body. As you study astronomical objects, pay special attention to their densities.

MASS | ENERGY | TEMPERATURE AND HEAT | DENSITY | PRESSURE

■ **Table 7-2** | **The Most Abundant Elements in the Sun**

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.003	0.1

silicon, iron, and aluminum. Even the most eminent astronomers dismissed Payne's result as illusory. Faced with this pressure and realizing that as a female scientist in the 1920s she faced an uphill battle, Payne could not press her discovery.

By 1929, astronomers generally understood the importance of temperature on measurements of composition derived from stellar spectra. At that point, they recognized that stars are mostly hydrogen and helium, but Payne received no credit.

Payne worked for many years as a staff astronomer at the Harvard College Observatory with no formal position on the faculty. She married Russian astronomer Sergei Gaposchkin in 1934 and was afterward known as Cecilia Payne-Gaposchkin. In 1956, Harvard accepted women to its faculty, and Payne-Gaposchkin was appointed a full professor and made chair of the Harvard astronomy department. By that time, the importance of her research 30 years earlier had come to be widely recognized.

Cecilia Payne-Gaposchkin's work on the chemical composition of the stars illustrates the importance of fully understanding the interaction between light and matter. It was her detailed understanding of the physics that led her to the correct composition. As you turn your attention to other information that can be derived from stellar spectra, you will again discover the importance of understanding light.

The Doppler Effect

Surprisingly, one of the pieces of information hidden in a spectrum is the velocity of the light source. Astronomers can measure the wavelengths of the lines in a star's spectrum and find the velocity of the star. The **Doppler effect** is the apparent change in the wavelength of radiation caused by the motion of the source.

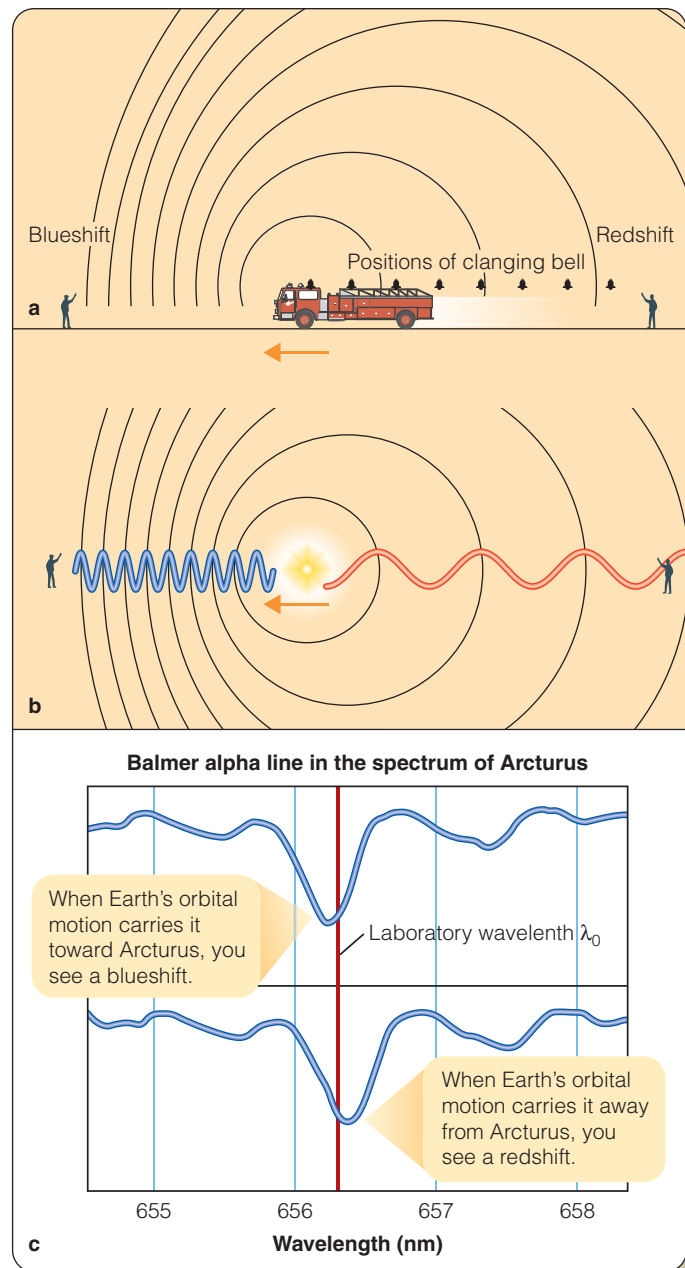
When astronomers talk about the Doppler effect, they are talking about a shift in the wavelength of electromagnetic radiation. But the Doppler shift can occur in any form of wave phenomena, including sound waves, so you probably hear the Doppler effect every day without noticing.

The pitch of a sound is determined by its wavelength. Sounds with long wavelengths have low pitches, and sounds with short wavelengths have higher pitches. You hear a Doppler shift every time a car or truck passes you and the pitch of its engine noise drops. Its sound is shifted to shorter wavelengths and higher pitches while it is approaching and is shifted to longer wavelengths and lower pitches after it passes.

To see why the sound waves are shifted in wavelength, consider a fire truck approaching you with a bell clanging once a second. When the bell clangs, the sound travels ahead of the truck to reach your ears. One second later, the bell clangs again, but, during that one second, the fire truck has moved closer to you, so the bell is closer at its second clang. Now the sound has a shorter distance to travel and reaches your ears a little sooner than it would have if the fire truck were not approaching. If you timed the clangs, you would find that you heard them slightly less than one second apart. After the fire truck passes you and is moving away, you hear the clangs sounding slightly more than one second apart because now each successive clang of the bell occurs farther from you and the sound travels farther to reach your ears.

■ Figure 7-11a shows a fire truck moving toward one observer and away from another observer. The position of the bell at each clang is shown by a small black bell. The sound of the clangs spreading outward is represented by black circles. You can see how the clangs are squeezed together ahead of the fire truck and stretched apart behind. If the fire truck has a siren instead of a bell, the sound coming from the siren will be a wave with a series of compressions and un-compressions. If the truck and siren are moving toward an observer, the compressions and un-compressions of the siren's sound wave will arrive more often— at a higher frequency— than if the truck were not moving, and the observer will hear the siren at a higher pitch than the same siren when it is stationary.

Now you can substitute a source of light for the clanging bell or wailing siren (Figure 7-11b). Imagine the light source emitting waves continuously as it approaches you. Each time the source emits the peak of a wave, it will be slightly closer to you than when it emitted the peak of the previous wave. From your vantage point, the successive peaks of the wave will seem closer together in the same way that the clangs of the bell seemed closer together. The light will appear to have a shorter wavelength, making it slightly bluer. Because the light is shifted slightly toward the blue end of the spectrum, this is called a **blueshift**. After the light source has passed you and is moving away, the peaks of successive waves seem farther apart, so the light has a longer wavelength and is redder. This is a **redshift**. The shifts are



■ **Figure 7-11**

The Doppler effect. (a) The clanging bell on a moving fire truck produces sounds that move outward (black circles). An observer ahead of the truck hears the clangs closer together, while an observer behind the truck hears them farther apart. Similarly, the sound waves from a siren on an approaching truck will be received more often, and thus be heard with a higher tone, than a stationary truck, and the siren will have a lower tone if it is going away. (b) A moving source of light emits waves that move outward (black circles). An observer toward whom the light source is moving observes a shorter wavelength (a blueshift), and an observer for whom the light source is moving away observes a longer wavelength (a redshift). (c) Absorption lines in the spectrum of the bright star Arcturus are shifted to the blue in winter, when Earth's orbital motion carries it toward the star, and to the red in summer when Earth moves away from the star.

much too small to change the color of a star, but they are easily detected in spectra.

The terms *redshift* and *blueshift* are used to refer to any range of wavelengths. The light does not actually have to be red or blue, and the terms apply equally to wavelengths in other parts of the electromagnetic spectrum such as X-rays and radio waves. *Red* and *blue* refer to the direction of the shift, not to actual color.

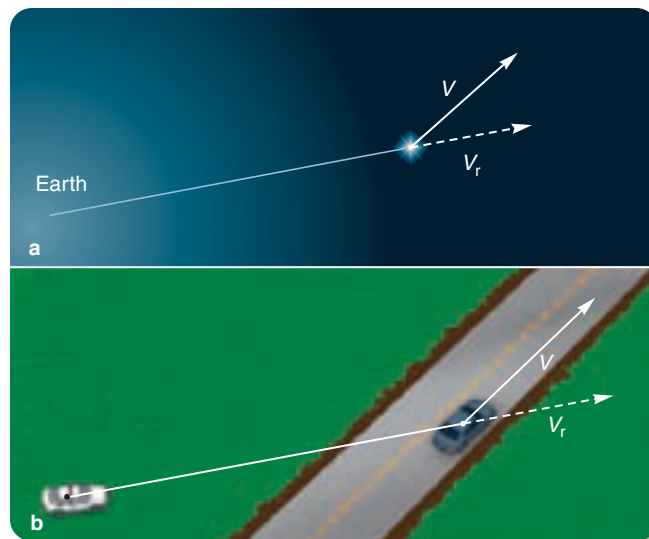
The amount of change in wavelength, and thus the magnitude of the Doppler shift, depends on the velocity of the source. A moving car has a smaller Doppler shift than a jet plane, and a slow-moving star has a smaller Doppler shift than one that is moving more quickly. You can measure the velocity of a star by measuring the size of its Doppler shift. If a star is moving toward Earth, it has a blue shift and each of its spectral lines is shifted very slightly toward shorter wavelengths. If it is receding from Earth, it has a red shift. The next section will show how astronomers can convert Doppler shifts into velocities.

When you think about the Doppler effect, it is important to understand two things. Earth itself moves, so a measurement of a Doppler shift really measures the relative motion between Earth and the star. Figure 7-11c shows the Doppler effect in two spectra of the star Arcturus. Lines in the top spectrum are slightly blueshifted because the spectrum was recorded when Earth, in the course of its orbit, was moving toward Arcturus. Lines in the bottom spectrum are redshifted because it was recorded six months later, when Earth was moving away from Arcturus. To find the true motion of Arcturus, astronomers must subtract the motion of Earth.

The second point to remember is that the Doppler shift is sensitive only to the part of the velocity directed away from you or toward you—the **radial velocity** (V_r) (■ Figure 7-12a). You cannot use the Doppler effect to detect any part of the velocity that is perpendicular to your line of sight. A star moving to the left, for example, would have no blueshift or redshift because its distance from Earth would not be decreasing or increasing. This is why police using radar guns park right next to the highway (Figure 7-12b). They want to measure your full velocity as you drive past, not just part of your velocity.

Calculating the Doppler Velocity

It is easy to calculate the radial velocity of an object from its Doppler shift. The formula is a simple proportion relating the



■ **Figure 7-12**

(a) From Earth, astronomers can use the Doppler effect to measure the radial velocity (V_r) of a star, but they cannot measure its true velocity, V , through space. (b) Police radar can measure only the radial part of your velocity (V_r) as you drive down the highway, not your true velocity along the pavement (V). That is why police using radar should never park far from the highway. This police car is poorly placed to make a good measurement.

radial velocity V_r divided by the speed of light c , to the change in wavelength, λ , divided by the un-shifted wavelength, λ_0 :

$$\frac{V_r}{c} = \frac{\Delta\lambda}{\lambda_0}$$

For example, suppose you observed a line in a star's spectrum with a wavelength of 600.1 nm. Laboratory measurements show that the line should have a wavelength of 600 nm. That is, its un-shifted wavelength is 600 nm. What is the star's radial velocity? First note that the change in wavelength is 0.1 nm:

$$\frac{V_r}{c} = \frac{0.1}{600} = 0.000167$$

Multiplying by the speed of light, 3.00×10^5 km/s, gives the radial velocity, 50 km/s. Because the wavelength is shifted to the red (lengthened), the star must be receding.

What Are We? Stargazers

Do you suppose chickens ever look at the sky and wonder what the stars are?

Probably not. Chickens are very good at the chicken business, but they are not known for big brains and deep thought. Humans, in contrast, have highly evolved, sophisticated brains and are extremely curious. In fact, curiosity may be the most reliable characteristic of intelligence, and curiosity about the stars is a natural extension of our continual attempts to understand the world around us.

For early astronomers like Copernicus and Kepler, the stars were just points of light. There seemed to be no way to learn anything about them. Galileo's telescope revealed surprising details about the planets; but, even viewed through a large telescope, the stars are just points of light. Even when later astronomers began to assume that the stars were other suns, the stars seemed forever beyond human knowledge.

As you have seen, the key is understanding how light interacts with matter. In the

last 150 years or so, scientists have discovered how atoms and light interact to form spectra, and astronomers have applied those discoveries to the ultimate object of human curiosity—the stars.

Chickens may never wonder what the stars are, or even wonder what chickens are, but humans are curious animals, and we do wonder about the stars and about ourselves. Our yearning to understand the stars is just part of our quest to understand what we are.

Study and Review

Summary

- ▶ An atom consists of a **nucleus (p. 123)** surrounded by a cloud of **electrons (p. 123)**. The nucleus is made up of positively charged **protons (p. 123)** and uncharged **neutrons (p. 123)**.
- ▶ The number of protons in an atom determines which element it is. Atoms of the same element (that is, having the same number of protons) with different numbers of neutrons are called **isotopes (p. 124)**.
- ▶ A neutral atom is surrounded by a number of negatively charged electrons equal to the number of protons in the nucleus. An atom that has lost or gained an electron is said to be **ionized (p. 124)** and is called an **ion (p. 124)**.
- ▶ Two or more atoms joined together form a **molecule (p. 124)**.
- ▶ The electrons in an atom are attracted to the nucleus by the **Coulomb force (p. 124)**. As described by **quantum mechanics (p. 124)**, the **binding energy (p. 124)** that holds electrons in an atom is limited to certain energies, and that means the electrons may occupy only certain **permitted orbits (p. 124)**.
- ▶ The size of an electron's orbit depends on its energy, so the orbits can be thought of as **energy levels (p. 126)** with the lowest possible energy level known as the **ground state (p. 126)**.
- ▶ An **excited atom (p. 126)** is one in which an electron is raised to a higher orbit by a collision between atoms or the absorption of a photon of the proper energy.
- ▶ The agitation among the atoms and molecules of an object is called **thermal energy (p. 127)**, and the flow of thermal energy is **heat (p. 127)**. In contrast, **temperature (p. 127)** refers to the intensity of the agitation and can be expressed on the **Kelvin temperature scale (p. 127)**, which gives temperature above **absolute zero (p. 127)**.
- ▶ Collisions among the particles in a body accelerate electrons and cause the emission of **blackbody radiation (p. 127)**. The hotter an object is, the more it radiates and the shorter is its **wavelength of maximum intensity, λ_{max} (p. 128)**. This allows astronomers to estimate the temperatures of stars from their colors.
- ▶ **Density (p. 137)** is a measure of the amount of matter in a given volume.
- ▶ **Kirchhoff's laws (p. 132)** explain that a hot solid, liquid, or dense gas emits electromagnetic radiation at all wavelengths and produces a **continuous spectrum (p. 132)**. An excited low-density gas produces an **emission (bright-line) spectrum (p. 132)** containing **emission lines (p. 132)**. A light source viewed through a low-density gas produces an **absorption (dark-line) spectrum (p. 132)** containing **absorption lines (p. 132)**.
- ▶ An atom can emit or absorb a photon when an electron makes a **transition (p. 133)** between orbits.
- ▶ Because orbits of only certain energy differences are permitted in an atom, photons of only certain wavelengths can be absorbed or emitted. Each kind of atom has its own characteristic set of spectral lines. The hydrogen atom has the **Lyman (p. 133) series** of lines in the ultraviolet, the **Balmer series (p. 133)** partially in the visible, and the **Paschen series (p. 133)** (plus others) in the infrared.
- ▶ The strength of spectral lines depends on the temperature of the star. For example, in cool stars, the Balmer lines are weak because atoms are not excited out of the ground state. In hot stars, the Balmer lines are weak because atoms are excited to higher orbits or are ionized. Only at medium temperatures are the Balmer lines strong.
- ▶ A star's **spectral class (or type) (p. 131)** is determined by the absorption lines in its spectrum. The resulting **spectral sequence (p. 131)**, OBAFGKM, is important because it is a temperature

sequence. By classifying a star, the astronomer learns the temperature of the star's surface.

- ▶ Long after the spectral sequence was created, astronomers found the **L dwarfs (p. 135)** and **T dwarfs (p. 135)** at temperatures even cooler than the M stars.
- ▶ A spectrum can tell you the chemical composition of the stars. The presence of spectral lines of a certain element shows that that element must be present in the star, but you must proceed with care. Lines of a certain element may be weak or absent if the star is too hot or too cool even if that element is present in the star's atmosphere.
- ▶ The **Doppler effect (p. 137)** can provide clues to the motions of the stars. When a star is approaching, you observe slightly shorter wavelengths, a **blueshift (p. 138)**, and when it is receding, you observe slightly longer wavelengths, a **redshift (p. 138)**. This Doppler effect reveals a star's **radial velocity, V_r (p. 139)**, that part of its velocity directed toward or away from Earth.

Review Questions

1. Why might you say that atoms are mostly empty space?
2. What is the difference between an isotope and an ion?
3. Why is the binding energy of an electron related to the size of its orbit?
4. Explain why ionized calcium can form absorption lines, but ionized hydrogen cannot.
5. Describe two ways an atom can become excited.
6. Why do different atoms have different lines in their spectra?
7. Why does the amount of blackbody radiation emitted depend on the temperature of the object?
8. Why do hot stars look bluer than cool stars?
9. What kind of spectrum does a neon sign produce?
10. Why are Balmer lines strong in the spectra of medium-temperature stars and weak in the spectra of hot and cool stars?
11. Why are titanium oxide features visible in the spectra of only the coolest stars?
12. Explain the similarities among Table 7-1, Figure 7-7c, Figure 7-8, and Figure 7-9.
13. Explain why the presence of spectral lines of a given element in the solar spectrum tells you that element is present in the sun, but the absence of the lines would not necessarily mean the element is absent from the sun.
14. Why does the Doppler effect detect only radial velocity?
15. How can the Doppler effect explain shifts in both light and sound?
16. **How Do We Know?** How is the world you see around you determined by a world you cannot see?

Discussion Questions

1. In what ways is the model of an atom a scientific model? In what ways is it incorrect?
2. Can you think of classification systems used to simplify what would otherwise be complex measurements? Consider foods, movies, cars, grades, and clothes.

Problems

1. Human body temperature is about 310 K (3.10×10^2 K, or 98.6°F). At what wavelength do humans radiate the most energy? What kind of radiation do we emit?

2. If a star has a surface temperature of 20,000 K (2.00×10^4 K), at what wavelength will it radiate the most energy?
3. Infrared observations of a star show that it is most intense at a wavelength of 2000 nm (2.00×10^3 nm). What is the temperature of the star's surface?
4. If you double the temperature of a blackbody, by what factor will the total energy radiated per second per square meter increase?
5. If one star has a temperature of 6000 K and another star has a temperature of 7000 K, how much more energy per second will the hotter star radiate from each square meter of its surface?
6. Electron orbit transition A produces light with a wavelength of 500 nm. Transition B involves twice as much energy as A. What wavelength light does it produce?
7. Determine the temperatures of the following stars based on their spectra. Use Figure 7-7c.
 - a. medium-strength Balmer lines, strong helium lines
 - b. medium-strength Balmer lines, weak ionized-calcium lines
 - c. strong TiO bands
 - d. very weak Balmer lines, strong ionized-calcium lines
8. To which spectral classes do the stars in Problem 7 belong?
9. In a laboratory, the Balmer beta line has a wavelength of 486.1 nm. If the line appears in a star's spectrum at 486.3 nm, what is the star's radial velocity? Is it approaching or receding?
10. The highest-velocity stars an astronomer might observe have velocities of about 400 km/s (4.00×10^2 km/s). What change in wavelength would this cause in the Balmer gamma line? (*Hint:* Wavelengths are given on page 133.)

Learning to Look

1. Consider Figure 7-3. When an electron in a hydrogen atom moves from the third orbit to the second orbit, the atom emits a Balmer-alpha photon in the red part of the spectrum. In what part of the spectrum would you look to find the photon emitted when an electron in a helium atom makes the same transition?
2. Where should the police car in Figure 7-12 have parked to make a good measurement?
3. The nebula shown below contains mostly hydrogen excited to emit photons. What kind of spectrum would you expect this nebula to produce?

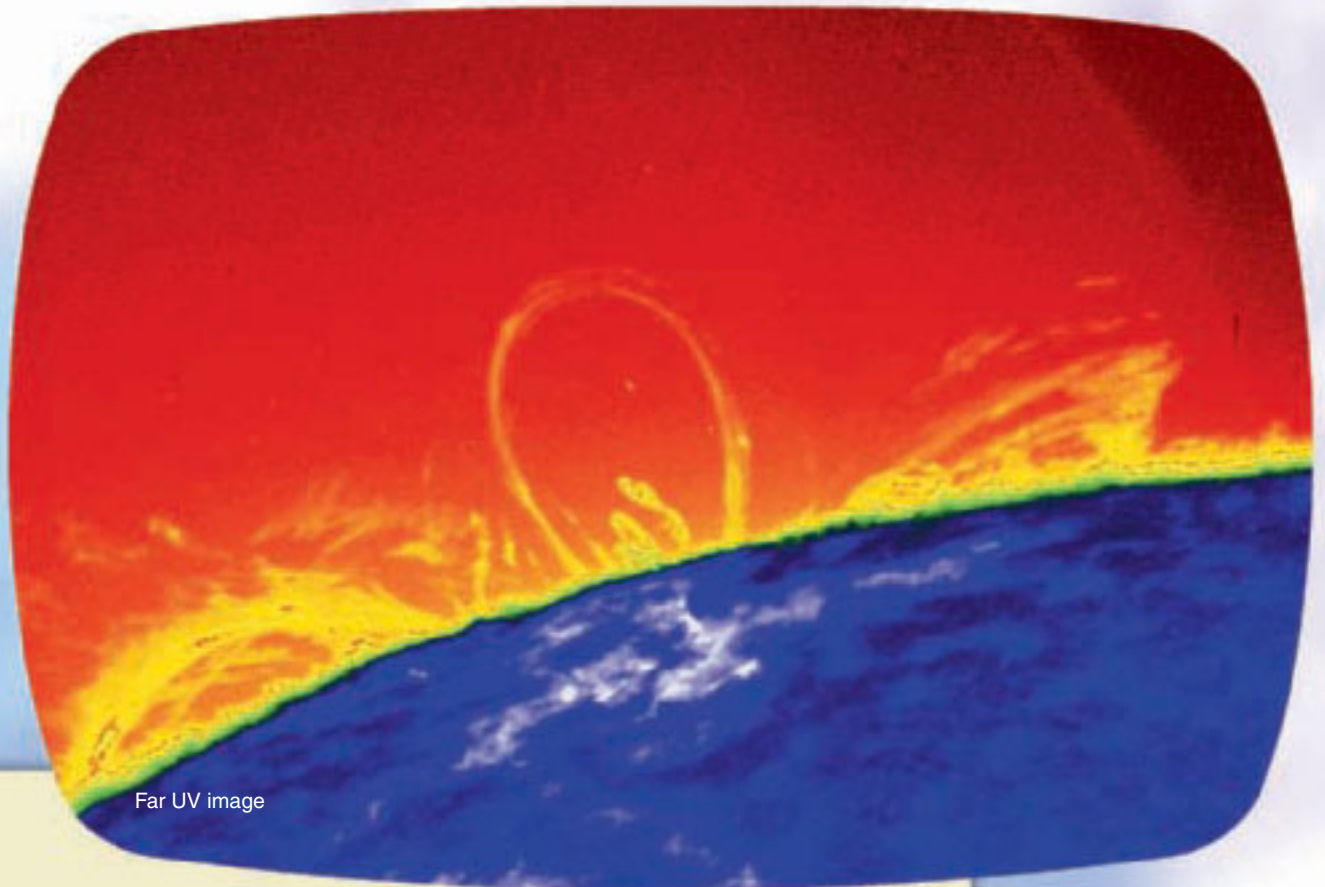


T. Rector, University of Alaska, and WYIN/NUR0/AURA/NSF

4. If the nebula in the image here crosses in front of the star, and the nebula and star have different radial velocities, what might the spectrum of the star look like?

8

The Sun



Far UV image

Guidepost

The sun is the source of light and warmth in our solar system, so it is a natural object of human curiosity. It is also the one star that is most clearly visible from Earth. The interaction of light and matter, which you studied in Chapter 7, can reveal the secrets of the sun and introduce you to the stars.

In this chapter, you will discover how the analysis of the solar spectrum can paint a detailed picture of the sun's atmosphere and how basic physics has solved the mystery of the sun's core. Here you will answer four essential questions:

— **What do you see when you look at the sun?**

— **How does the sun make its energy?**

— **What are the dark sunspots?**

— **Why does the sun go through a cycle of activity?**

Although this chapter is confined to the center of the solar system, it introduces you to a star and leads your thoughts onward among the stars and galaxies that fill the universe.

This far-ultraviolet image of the sun made from space has been enhanced and rendered in false color to reveal complex structure on the surface and clouds of gas trapped in arched magnetic fields above the surface. (NASA/TRACE)

All cannot live on the piazza, but everyone may enjoy the sun.

— ITALIAN PROVERB

A WIT ONCE REMARKED that solar astronomers would know a lot more about the sun if it were farther away. The sun is so close that Earth's astronomers can see swirling currents of gas and arched bridges of magnetic force. The details seem overwhelming. But the sun is just an average star; and, in a sense, it is a simple object. It is made up almost entirely of the gases hydrogen and helium confined by its own gravity in a sphere 109 times Earth's diameter (**Celestial Profile 1**). The gases of the sun's surface are hot and radiate the light and heat that make life possible on Earth. That solar atmosphere is where you can begin your exploration.

8-1 The Solar Atmosphere

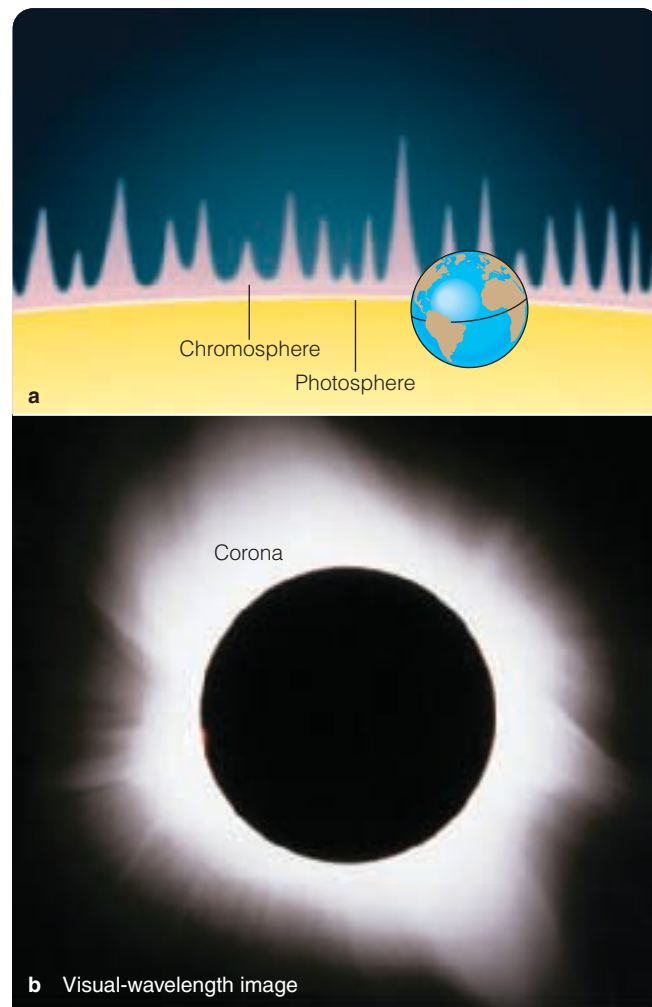
THE SUN'S ATMOSPHERE is made up of three layers. The visible surface is the *photosphere*, and above that are the *chromosphere* and the *corona*. (You first met these terms in Chapter 3 when you learned about solar eclipses.)

When you look at the sun you see a hot, glowing surface with a temperature of about 5800 K. At that temperature, every square millimeter of the sun's surface must be radiating more energy than a 60-watt light bulb. With all that energy radiating into space, the sun's surface would cool rapidly if energy did not flow up from the interior to keep the surface hot, so simple logic tells you that energy in the form of heat is flowing outward from the sun's interior. Not until the 1930s did astronomers understand that the sun makes its energy by nuclear reactions at the center. Those nuclear reactions are discussed in detail later in this chapter.

For now, you can consider the sun's atmosphere in its quiescent, average state. Later you can add the details of its continuous activity as heat flows up from the sun's interior and makes the outer layers churn like a pot of boiling soup.

The Photosphere

The visible surface of the sun looks like a smooth layer of gas marked only by a few dark **sunspots** that come and go over a few weeks. Although the photosphere seems to be a distinct surface, it is not solid. In fact, the sun is gaseous from its outer atmosphere right down to its center. The photosphere is the thin layer of gas from which Earth receives most of the sun's light. It is less than 500 km deep, and if the sun magically shrank to the size of a bowling ball, the photosphere would be no thicker than a layer of tissue paper wrapped around the ball (■ Figure 8-1).



■ **Figure 8-1**

(a) A cross section at the edge of the sun shows the relative thickness of the photosphere and chromosphere. Earth is shown for scale. On this scale, the disk of the sun would be more than 1.5 m (5 ft) in diameter. The corona extends from the top of the chromosphere to great height above the photosphere. (b) This photograph, made during a total solar eclipse, shows only the inner part of the corona. (Daniel Good)

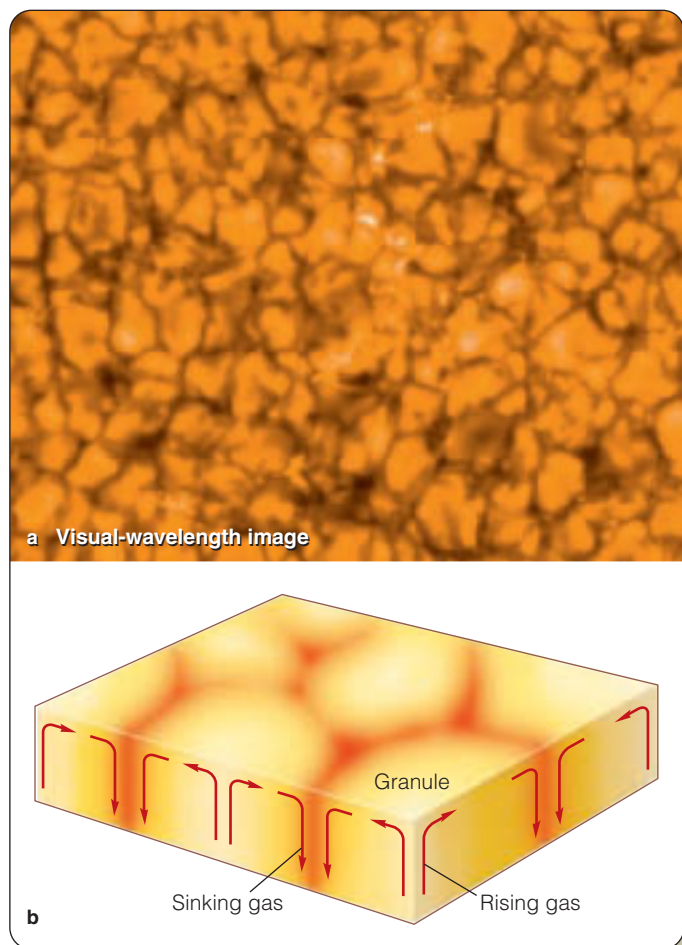
The photosphere is the layer in the sun's atmosphere that is dense enough to emit plenty of light but not so dense that the light can't escape. Below the photosphere, the gas is denser and hotter and therefore radiates plenty of light, but that light cannot escape from the sun because it is blocked by the outer layers of gas. So you cannot detect light from these deeper layers. Above the photosphere, the gas is less dense and so is unable to radiate much light.

Although the photosphere appears to be substantial, it is really a very-low-density gas. Even in its deepest and densest layers, the photosphere is less than 1/3000 as dense as the air you breathe. To find gases as dense as the air at Earth's surface, you would have to descend about 70,000 km below the photosphere,

about 10 percent of the way to the sun's center. With fantastically efficient insulation, you could fly a spaceship right through the photosphere.

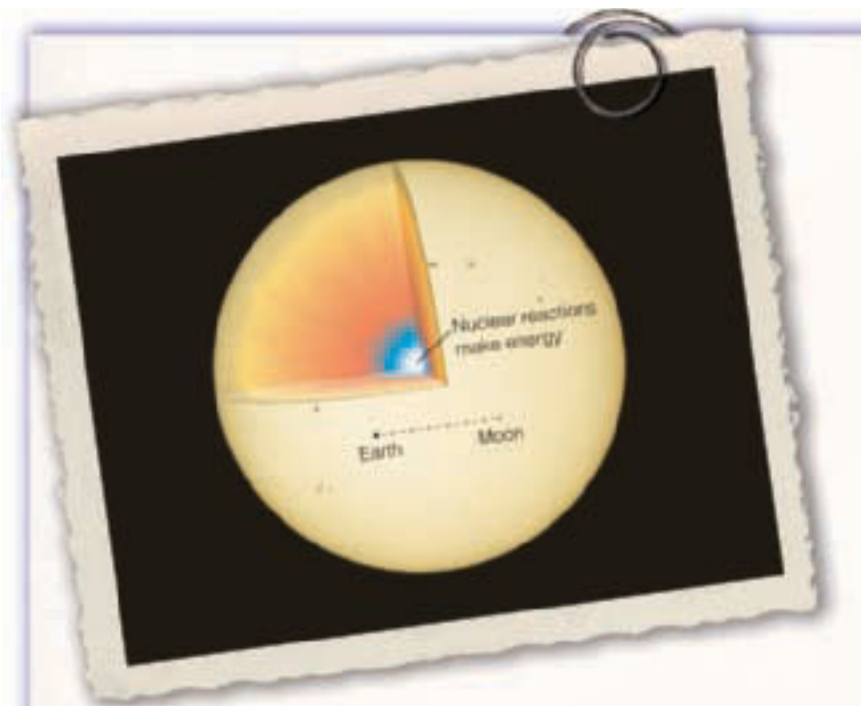
The spectrum of the sun is an absorption spectrum, and that can tell you a great deal about the photosphere. You know from Kirchhoff's third law that an absorption spectrum is produced when the source of a continuous spectrum is viewed through a gas. The deeper layers of the photosphere are dense enough to produce a continuous spectrum, but atoms in the photosphere absorb photons of specific wavelengths, producing absorption lines of hydrogen, helium, and other elements.

In good photographs, the photosphere has a mottled appearance because it is made up of dark-edged regions called granules. The overall pattern is called **granulation** (■ Figure 8-2a). Each granule is about the size of Texas and lasts for only 10 to 20 minutes before fading, shrinking, and being replaced by a new



■ **Figure 8-2**

(a) This ultra-high-resolution image of the photosphere shows granulation. The largest granules here are about the size of Texas. (b) This model explains granulation as the tops of rising convection currents just below the photosphere. Heat flows upward as rising currents of hot gas and downward as sinking currents of cool gas. The rising currents heat the solar surface in small regions seen from Earth as granules.



This visible image of the sun shows a few sunspots and is cut away to show the location of energy generation at the sun's center. The Earth–moon system is shown for scale. (Daniel Good)

Celestial Profile 1: The Sun

From Earth:

Average distance from Earth	1.000 AU (1.496×10^8 km)
Maximum distance from Earth	1.017 AU (1.521×10^8 km)
Minimum distance from Earth	0.983 AU (1.471×10^8 km)
Average angular diameter	0.53° (32 arc minutes)
Period of rotation	25.4 days at equator
Apparent visual magnitude	−26.74

Characteristics:

Radius	6.96×10^5 km
Mass	1.99×10^{30} kg
Average density	1.41 g/cm ³
Escape velocity at surface	618 km/s
Luminosity	3.83×10^{26} J/s
Surface temperature	5800 K
Central temperature	15×10^6 K
Spectral type	G2 V
Absolute visual magnitude	4.83

Personality Profile:

In Greek mythology, the sun was carried across the sky in a golden chariot pulled by powerful horses and guided by the sun god Helios. When Phaeton, the son of Helios, drove the chariot one day, he lost control of the horses, and Earth was nearly set ablaze before Zeus smote Phaeton from the sky. Even in classical times, people understood that life on Earth depends critically on the sun.

granule. Spectra of granules show that the centers are a few hundred degrees hotter than the edges, and Doppler shifts reveal that the centers are rising and the edges are sinking at speeds of about 0.4 km/s.

From this evidence, astronomers recognize granulation as the surface effects of convection just below the photosphere. **Convection** occurs when hot fluid rises and cool fluid sinks, as when, for example, a convection current of hot gas rises above a candle flame. You can watch convection in a liquid by adding a bit of cool non-dairy creamer to an unstirred cup of hot coffee. The cool creamer sinks, warms, expands, rises, cools, contracts, sinks again, and so on, creating small regions on the surface of the coffee that mark the tops of convection currents. Viewed from above, these regions look much like solar granules.

In the sun, rising currents of hot gas heat small regions of the photosphere, which, being slightly hotter, emit more blackbody radiation and look brighter. The cool sinking gas of the edges emits less light and thus looks darker (Figure 8-2b). The presence of granulation is clear evidence that energy is flowing upward through the photosphere.

Spectroscopic studies of the solar surface have revealed another less obvious kind of granulation. **Supergranules** are regions a little over twice Earth's diameter that include about 300 granules each. These supergranules are regions of very slowly rising currents that last a day or two. They appear to be produced by larger gas currents that lie deeper under the photosphere.

The edge, or **limb**, of the solar disk is dimmer than the center (see the figure in Celestial Profile 1). This **limb darkening** is caused by the absorption of light in the photosphere. When you look at the center of the solar disk, you are looking directly down into the sun, and you see deep, hot, bright layers in the photosphere. In contrast, when you look near the limb of the solar disk, you are looking at a steep angle to the surface and cannot see as deeply. The photons you see come from shallower, cooler, dimmer layers in the photosphere. Limb darkening proves that the temperature in the photosphere increases with depth, yet another confirmation that energy is flowing up from below.

The Chromosphere

Above the photosphere lies the chromosphere. Solar astronomers define the lower edge of the chromosphere as lying just above the visible surface of the sun, with its upper regions blending gradually with the corona. You can think of the chromosphere as an irregular layer with a depth on average less than Earth's diameter (see Figure 8-1). Because the chromosphere is roughly 1000 times fainter than the photosphere, you can see it with your unaided eyes only during a total solar eclipse when the moon covers the brilliant photosphere. Then, the chromosphere

flashes into view as a thin line of pink just above the photosphere. The word *chromosphere* comes from the Greek word *chroma*, meaning "color." The pink color is produced by the combined light of three bright emission lines—the red, blue, and violet Balmer lines of hydrogen.

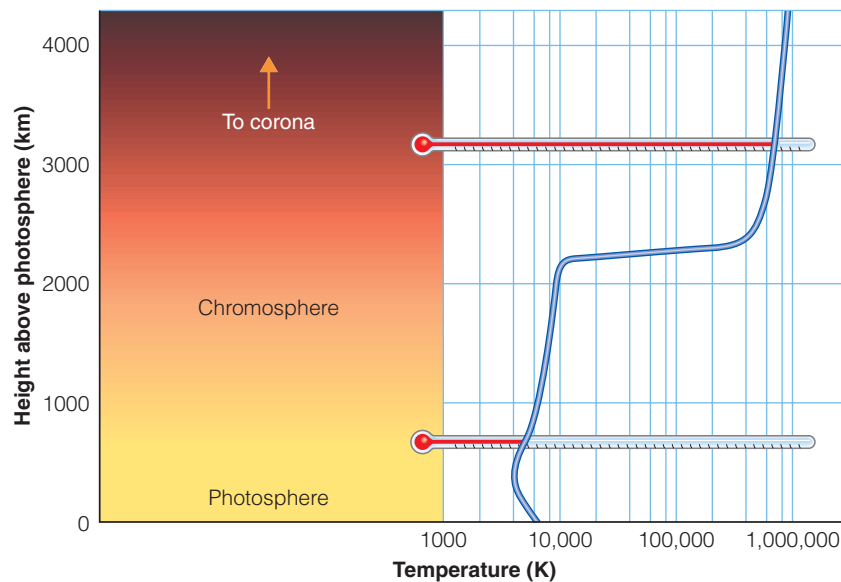
Astronomers know a great deal about the chromosphere from its spectrum. The chromosphere produces an emission spectrum, and Kirchhoff's second law tells you it must be an excited, low-density gas. The chromosphere is about 10^8 times less dense than the air you breathe.

Spectra reveal that atoms in the lower chromosphere are ionized, and atoms in the higher layers of the chromosphere are even more highly ionized. That is, they have lost more electrons. Hydrogen atoms contain only one electron, but atoms like calcium and iron contain many more, and at high enough temperatures they can lose a number of electrons and become highly ionized. From the ionization state of the gas, astronomers can find the temperature in different parts of the chromosphere. Just above the photosphere the temperature falls to a minimum of about 4500 K and then rises rapidly (■ Figure 8-3) to the extremely high temperatures of the corona. The upper chromosphere is hot enough to emit X-rays and can be studied by X-ray telescopes in space.

Solar astronomers can take advantage of some elegant physics to study the chromosphere. The gases of the chromosphere are transparent to nearly all visible light, but atoms in the gas are very good at absorbing photons of specific wavelengths. This produces certain dark absorption lines in the spectrum of the photosphere. A photon at one of those wavelengths is very

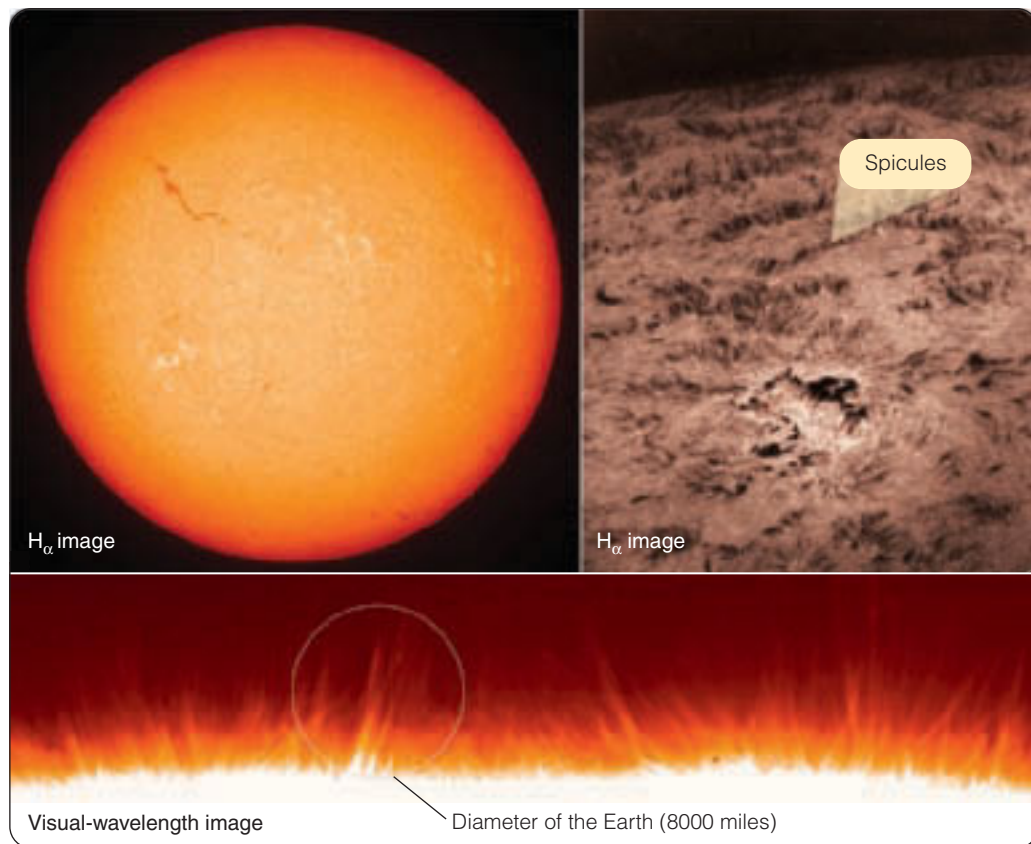
■ **Figure 8-3**

The chromosphere. If you could place thermometers in the sun's atmosphere, you would discover that the temperature increases from 5800 K at the photosphere to 1,000,000 K at the top of the chromosphere.



■ **Figure 8-4**

H_{α} filtergrams reveal complex structure in the chromosphere that cannot be seen at visual wavelengths, including spicules springing from the edges of supergranules over twice the diameter of Earth. Seen at the edge of the solar disk, spicules look like a burning prairie, but they are not at all related to burning. Compare with Figure 8-1. (BBSO; © 1971 NOAO/NSO; Hinode)



unlikely to escape from deeper layers. A **filtergram** is an image of the sun made using light in one of those dark absorption lines. Those photons can only have escaped from higher in the sun's atmosphere. In this way, filtergrams reveal detail in the upper layers of the chromosphere. Another way to study these high, hot layers of gas is to record solar images in the far-ultraviolet or in the X-ray part of the spectrum.

■ Figure 8-4 shows a filtergram made at the wavelength of the H_{α} Balmer line. This image shows complex structure in the chromosphere. **Spicules** are flamelike jets of gas extending upward into the chromosphere and lasting 5 to 15 minutes. Seen at the limb of the sun's disk, these spicules blend together and look like flames covering a burning prairie (Figure 8-1), but they are not flames at all. Spectra show that spicules are cooler gas from the lower chromosphere extending upward into hotter regions. Images at the center of the solar disk show that spicules spring up around the edge of supergranules like weeds around flagstones (Figure 8-4).

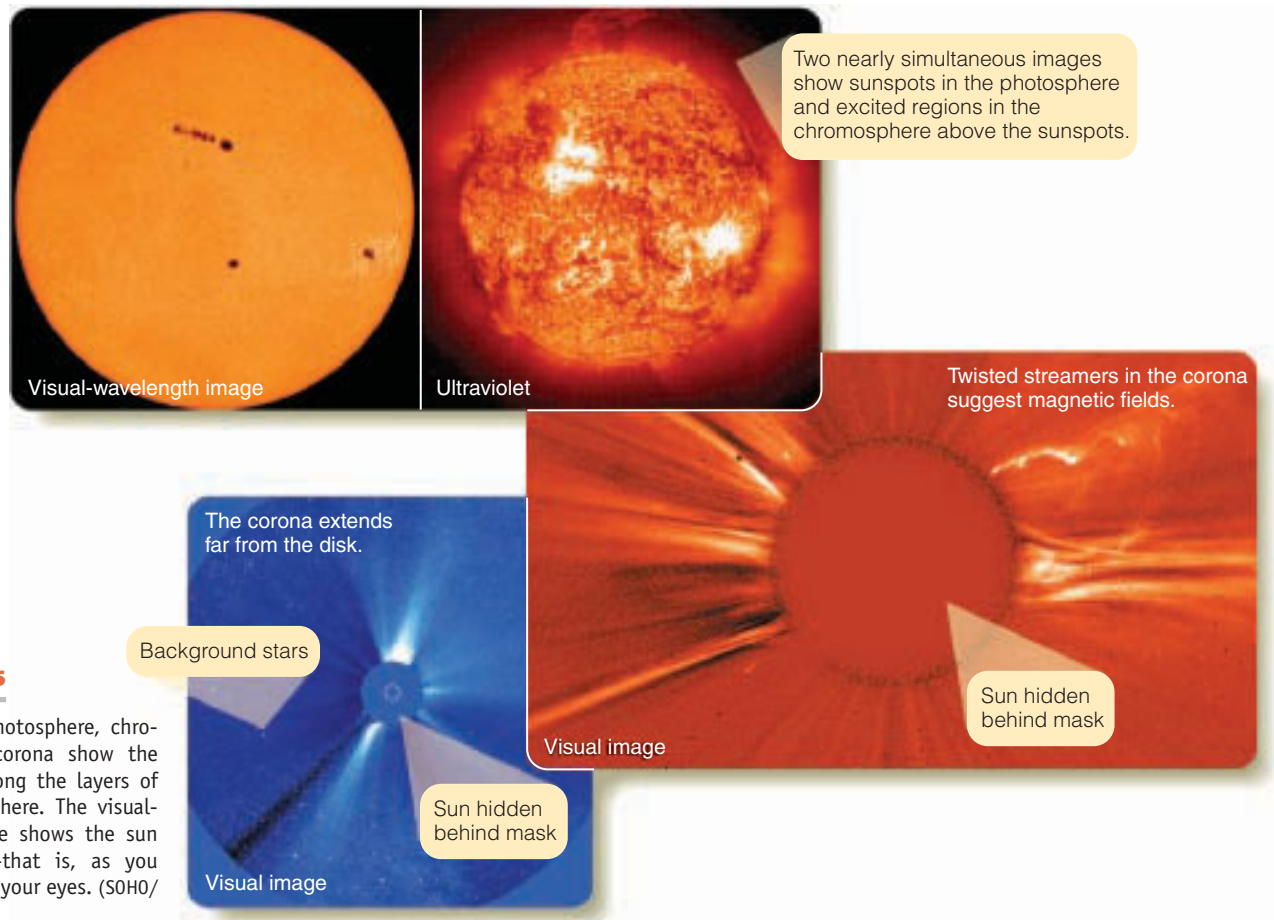
The Solar Corona

The outermost part of the sun's atmosphere is called the corona, after the Greek word for crown. The corona is so dim that, like the chromosphere, it is not visible in Earth's daytime sky because of the glare of scattered light from the sun's brilliant photosphere. During a total solar eclipse, the innermost parts of the corona are

visible to the unaided eye, as shown in Figure 8-1b. Observations made with specialized telescopes called **coronagraphs** can block the light of the photosphere and record the corona out beyond 20 solar radii, almost 10 percent of the way to Earth. Such images reveal streamers in the corona that follow magnetic lines of force in the sun's magnetic field (■ Figure 8-5).

The spectrum of the corona can tell you a great deal about the coronal gases and simultaneously illustrate how astronomers analyze a spectrum. Some of the light from the outer corona produces a spectrum with absorption lines that are the same as the photosphere's spectrum. This light is just sunlight reflected from dust particles in the corona. In contrast, some of the light from the corona produces a continuous spectrum that lacks absorption lines, and that happens when sunlight from the photosphere is scattered off free electrons in the ionized coronal gas. Because the coronal gas has a temperature over 1 million K and the electrons travel very fast, the reflected photons suffer large, random Doppler shifts that smear out absorption lines to produce a continuous spectrum.

Superimposed on the corona's continuous spectrum are emission lines of highly ionized gases. In the lower corona, the atoms are not as highly ionized as they are at higher altitudes, and this tells you that the temperature of the corona rises with altitude. Just above the chromosphere, the temperature is about 500,000 K, but in the outer corona the temperature can be 2 million K or more.



■ **Figure 8-5**

Images of the photosphere, chromosphere, and corona show the relationships among the layers of the sun's atmosphere. The visual-wavelength image shows the sun in white light—that is, as you would see it with your eyes. (SOHO/ESA/NASA)

The corona is exceedingly hot gas. In fact, as you learned earlier, the gas in the corona and upper chromosphere is so hot it can emit X-rays. Nevertheless, the coronal gas is not very bright. Its density is very low, only 10^6 atoms/cm³ in its lower regions. That is about 10^{12} times less dense than the air you breathe. In its outer layers the corona contains only 1 to 10 atoms/cm³, fewer than in the best vacuum in laboratories on Earth. Because of its low density, the hot gas does not emit much radiation.

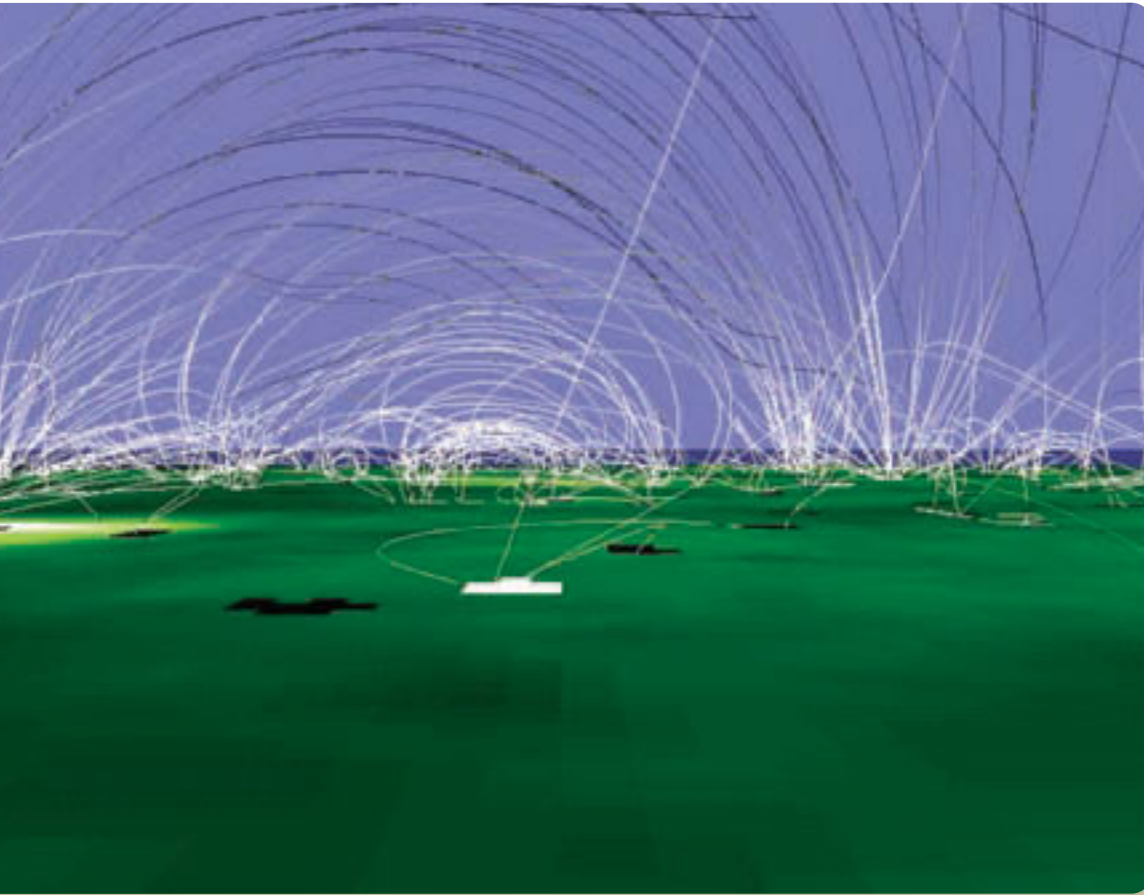
Astronomers have wondered for years how the corona and chromosphere can be so hot. Heat flows from hot regions to cool regions, never from cool to hot. So how can the heat from the photosphere, with a temperature of only 5800 K, flow out into the much hotter chromosphere and corona? Observations made by the SOHO satellite have mapped a **magnetic carpet** of looped magnetic fields extending up through the photosphere (■ Figure 8-6). Remember that the gas of the chromosphere and corona has a very low density, so it can't resist movement of the magnetic fields. Turbulence below the photosphere seems to flick the magnetic loops back and forth and whip the gas about, heating the gas. Furthermore, observations with the Hinode spacecraft have revealed magnetic waves generated by turbulence below the photosphere traveling up into the chromosphere and

corona and heating the gas. Because the gas in the corona has such a low density, it doesn't take much energy flowing outward as agitation in the magnetic fields to heat the corona to high temperature.

Ionized, low-density gas cannot cross magnetic fields, so where the sun's field loops back to the surface, the gas is trapped. However, some of the magnetic fields lead outward into space, and there the gas flows away from the sun in a breeze called the **solar wind**. Like an extension of the corona, the low-density gases of the solar wind blow past Earth at 300 to 800 km/s with gusts as high as 1000 km/s. Earth is bathed in the corona's hot breath.

Because of the solar wind, the sun is slowly losing mass, but this is only a minor loss for an object as massive as the sun. The sun loses about 10^7 tons per second, but that is only 10^{-14} of a solar mass per year. Later in life, the sun, like many other stars, will lose mass rapidly in a more powerful wind. You will see in future chapters how this affects the evolution of stars.

Do other stars have chromospheres, coronae, and stellar winds like the sun? Stars are so far away they never look like more than points of light, but ultraviolet and X-ray observations suggest that the answer is yes. The spectra of many stars contain emission lines in the far-ultraviolet that could have formed only



■ **Figure 8-6**

Flying through the magnetic carpet. This computer model shows an extreme-ultraviolet image of a section of the sun's lower corona (green) with black and white areas marking regions of opposite magnetic polarity. A mathematical model has drawn lines to show how the areas are linked by loops of magnetic force. The largest loops here could encircle Earth. (Stanford-Lockheed Institute for Space Research, Palo Alto, CA, and NASA GSFC)

in the low-density, high-temperature gases of a chromosphere and corona. Also, many stars are sources of X-rays, which appear to have been produced by the high-temperature gas in their chromospheres and coronae. This observational evidence gives astronomers good reason to believe that the sun, for all its complexity, is a typical star.

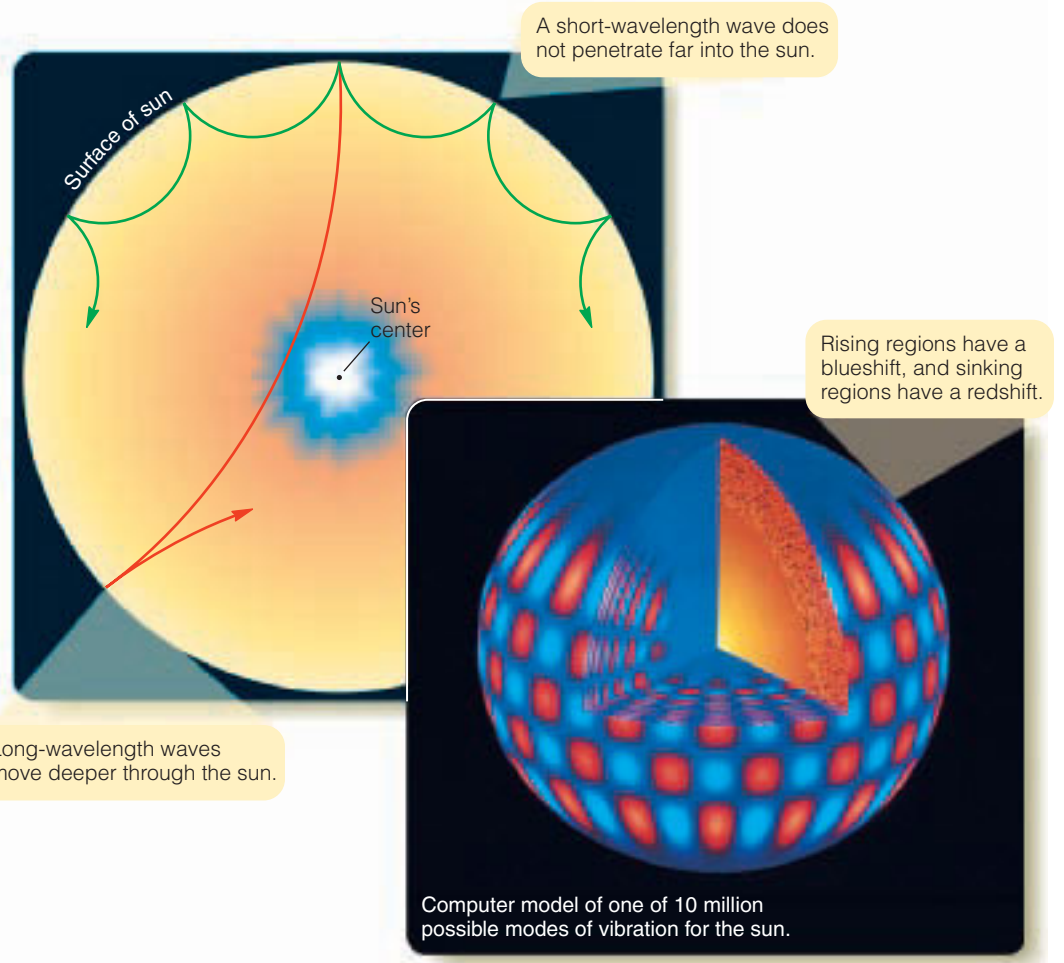
The layers of the solar atmosphere are all that astronomers can observe directly, but there are phenomena in those layers that reveal what it's like inside the sun—your next destination.

Below the Photosphere

Almost no light emerges from below the photosphere, so you can't see into the solar interior. However, solar astronomers can study naturally occurring vibrations in the sun to explore its depths in a process called **helioseismology**. Random convective movements of gas in the sun constantly produce vibrations—rumbles that would be much too low to hear with human ears even if your ears could survive a visit to the sun's atmosphere. Some of these vibrations resonate in the sun like sound waves in organ pipes. A vibration with a period of 5 minutes is strongest, but the periods range from 3 to 20 minutes. These are very, very low-pitched sounds!

Astronomers can detect these vibrations by observing Doppler shifts in the solar surface. As a vibrational wave travels down into the sun, the increasing density and temperature curve its path, and it returns to the surface, where it makes the photosphere heave up and down by small amounts—roughly plus or minus 15 km. Many of these vibrations occurring simultaneously cover the surface of the sun with a pattern of rising and falling regions that can be mapped using the Doppler effect (■ Figure 8-7). By observing these motions, astronomers can determine which vibrations resonate and become stronger and which become weaker. Short-wavelength waves penetrate less deeply and travel shorter distances than longer-wavelength waves, so the different wavelength vibrations explore different layers in the sun. Just as geologists can study Earth's interior by analyzing vibrations from earthquakes, so solar astronomers can use helioseismology to explore the sun's interior.

You can better understand how helioseismology works if you think of a duck pond. If you stood at the shore of a duck pond and looked down at the water, you would see ripples arriving from all parts of the pond. Because every duck on the pond contributes to the ripples, you could, in principle, study the ripples near the shore and draw a map showing the position and velocity



■ **Figure 8-7**

Helioseismology: The sun can vibrate in millions of different patterns or modes, and each mode corresponds to a different wavelength vibration penetrating to a different level. By measuring Doppler shifts as the surface moves gently up and down, astronomers can map the inside of the sun. (AURA/NOAO/NSF)

of every duck on the pond. Of course, it would be difficult to untangle the different ripples, so you would need lots of data and a big computer. Nevertheless, all of the information would be there, lapping at the shore.

Helioseismology demands huge amounts of data, so astronomers have used a network of telescopes around the world operated by the Global Oscillation Network Group (GONG). The network can observe the sun continuously for weeks at a time as Earth rotates. The sun never sets on GONG. The SOHO satellite in space can observe solar oscillations continuously and can detect motions as slow as 1 mm/s (0.002 mph). Solar astronomers can then use high-speed computers to separate the different patterns on the solar surface and measure the strength of the waves at many different wavelengths.

Helioseismology has allowed astronomers to map the temperature, density, and rate of rotation inside the sun. They have been able to map great currents of gas flowing below the photosphere and the development of sunspots before they become

visible in the photosphere. Helioseismology can even locate sunspots on the back side of the sun, sunspots that are not yet visible from Earth.

SCIENTIFIC ARGUMENT

What evidence leads astronomers to conclude that temperature increases with height in the chromosphere and corona?

Scientific arguments usually involve evidence, and in astronomy that means observations. Solar astronomers can observe the spectrum of the chromosphere, and they find that atoms there are more highly ionized (have lost more electrons) than atoms in the photosphere. Atoms in the corona are even more highly ionized. That must mean the chromosphere and corona are hotter than the photosphere.

Evidence is the key to understanding how science works. Now it is time to build a new argument. **What evidence leads astronomers to conclude that other stars have chromospheres and coronae like those of the sun?**

8-2 Nuclear Fusion in the Sun

LIKE SOAP BUBBLES, stars are structures balanced between opposing forces that individually would destroy them. The sun is a ball of hot gas held together by its own gravity. If it were not for the sun's gravity, the hot, high-pressure gas in the sun's interior would explode outward. Likewise, if the sun were not so hot, its gravity would compress it into a small dense body. In this section, you will discover how the sun generates its heat.

The sun is powered by nuclear reactions that occur near its center.* The energy keeps the interior hot and keeps the gas totally ionized. That is, the electrons are not attached to atomic nuclei, so the gas is an atomic soup of rapidly moving particles colliding with each other at high velocities. Nuclear reactions inside stars involve atomic nuclei, not whole atoms.

How exactly can the nucleus of an atom yield energy? The answer lies in the force that holds the nuclei together.

Nuclear Binding Energy

The sun generates its energy by breaking and reconnecting the bonds between the particles *inside* atomic nuclei. This is quite different from the way you would generate energy by burning wood in a fireplace. The process of burning wood extracts energy by breaking and rearranging chemical bonds among atoms in the wood. Chemical bonds are formed by the electrons in atoms, and you saw in Chapter 7 that the electrons are bound to the atoms by the electromagnetic force. So the chemical energy released when these bonds are broken and rearranged originates in the electromagnetic force.

There are only four forces in nature: the force of gravity, the electromagnetic force, the **weak force**, and the **strong force**. The weak force is involved in the radioactive decay of certain kinds of nuclear particles, and the strong force binds together atomic nuclei. The weak force and the strong force are both much stronger than either gravity or the electromagnetic force, but they are short-range forces that are effective only within the nuclei of atoms. Nuclear reactions break and reform the bonds that hold atomic nuclei together, so nuclear energy comes from the strong force. (In a later chapter you will learn that physicists have discovered the electromagnetic force and the weak force are actually different aspects of one force, and they have a goal of eventually finding a way to “unify” all four forces, including gravity, within one general mathematical description).

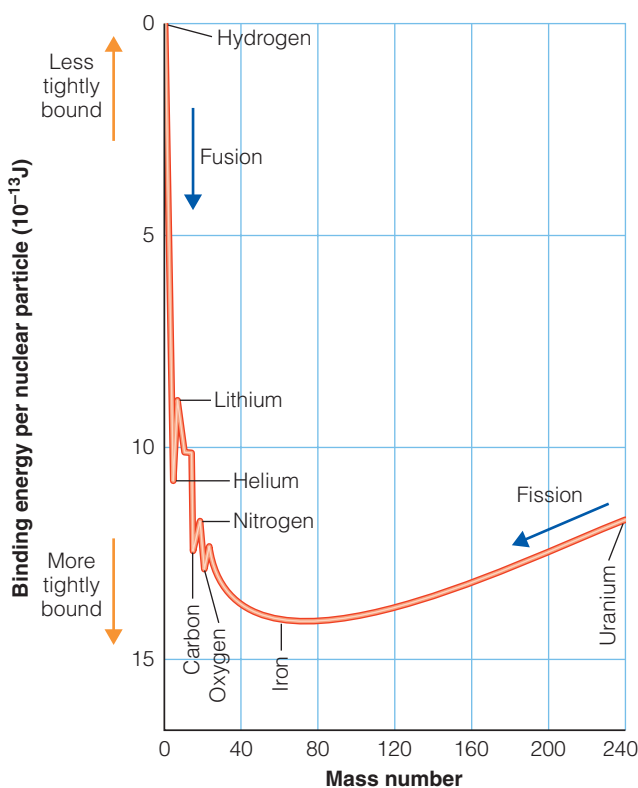
There are two ways to generate energy from atomic nuclei. Nuclear power plants on Earth generate energy through **nuclear fission** reactions that split uranium nuclei into less massive

*Astronomers sometimes use unhelpful words when they talk about nuclear reactions inside stars. They may use words like *burn* or *ignite*. What goes on inside stars is not related to simple burning but is comprised of nuclear reactions.

fragments. A uranium nucleus contains a total of 235 protons and neutrons, and when it decays, it splits into a range of possible fragments, each containing roughly half as many particles. Because the fragments that are produced are more tightly bound than the uranium nuclei, binding energy is released during uranium fission.

Stars don't use nuclear fission. They make energy in **nuclear fusion** reactions that combine light nuclei into heavier nuclei. The most common reaction inside stars, the one that occurs in the sun, fuses hydrogen nuclei (single protons) into helium nuclei, which contain two protons and two neutrons. Because the nuclei produced are more tightly bound than the original nuclei, energy is released.

■ Figure 8-8 shows how tightly different atomic nuclei are bound. The lower in the diagram, the more tightly the particles in a nucleus are held. Notice that both fusion and fission reactions move downward in the diagram toward more tightly bound nuclei. They both produce energy by releasing binding energy of atomic nuclei.



■ **Figure 8-8**

The red line in this graph shows the binding energy per particle, the energy that holds particles inside an atomic nucleus. The horizontal axis shows the atomic mass number of each element, the number of protons and neutrons in the nucleus. Both fission and fusion nuclear reactions move downward in the diagram (arrows), meaning the nucleus produced by a reaction is more tightly bound than the nuclei that went into the reaction. Iron has the most tightly bound nucleus, so no nuclear reactions can begin with iron and release energy.

Hydrogen Fusion

The sun fuses together four hydrogen nuclei to make one helium nucleus. Because one helium nucleus has 0.7 percent less mass than four hydrogen nuclei, it seems that some mass vanishes in the process. To see this, subtract the mass of a helium nucleus from the mass of four hydrogen nuclei:

$$\begin{array}{r} 4 \text{ hydrogen nuclei} = 6.693 \times 10^{-27} \text{ kg} \\ - 1 \text{ helium nucleus} = 6.645 \times 10^{-27} \text{ kg} \\ \hline \text{Difference in mass} = 0.048 \times 10^{-27} \text{ kg} \end{array}$$

This small amount of mass does not actually disappear but is converted to energy according to Einstein's famous equation:

$$\begin{aligned} E &= mc^2 \\ &= (0.048 \times 10^{-27} \text{ kg}) \times (3.0 \times 10^8 \text{ m/s})^2 \\ &= 0.43 \times 10^{-11} \text{ J} \end{aligned}$$

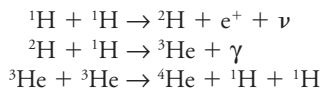
You can symbolize the fusion reactions in the sun with a simple nuclear reaction:



In this equation, ^1H represents a proton, the nucleus of a hydrogen atom, and ^4He represents the nucleus of a helium atom. The superscripts indicate the approximate weight of the nuclei (the number of protons plus the number of neutrons). The actual steps in the process are more complicated than this convenient summary suggests. Instead of waiting for four hydrogen nuclei to collide simultaneously, a highly unlikely event, the process normally proceeds step by step in a chain of reactions—the proton–proton chain.

The **proton–proton chain** is a series of three nuclear reactions that builds a helium nucleus by adding together protons. This process can only happen at temperatures above about 4 million K, and is efficient above 10 million K. The sun makes over 90 percent of its energy in this way.

The three steps in the proton–proton chain entail these reactions:



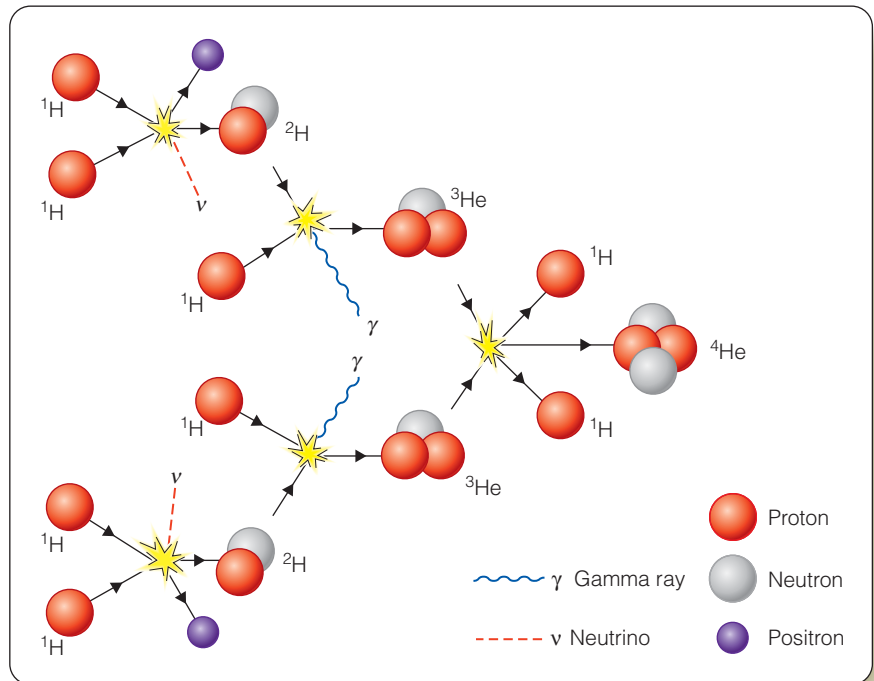
In the first reaction, two hydrogen nuclei (two protons) combine and emit a particle called a **positron**, e^+ (a positively charged electron), and a **neutrino**, ν (a subatomic particle having an extremely low mass and a velocity nearly equal to the velocity of light). The emission of the positively charged positron results from the conversion of one of the protons into a neutron, and that forms a heavy hydrogen nucleus called **deuterium**, which contains a proton and a neutron. In the second reaction, the heavy hydrogen nucleus absorbs another proton and, with the

emission of a gamma ray, γ , becomes a lightweight helium nucleus. Finally, two lightweight helium nuclei combine to form a nucleus of normal helium and two hydrogen nuclei. Because the last reaction needs two ^3He nuclei, the first and second reactions must occur twice (■ Figure 8-9). The net result of this chain reaction is the transformation of four hydrogen nuclei into one helium nucleus plus energy.

The energy appears in the form of gamma rays, positrons, neutrinos and the energy of motion of all the particles. The gamma rays are photons that are absorbed by the surrounding gas before they can travel more than a fraction of a millimeter. This heats the gas. The positrons produced in the first reaction combine with free electrons, and both particles vanish, converting their mass into gamma rays, which are absorbed and also help keep the gas hot. In addition, when fusion produces new nuclei, they fly apart at high velocity and collide with other particles. This energy of motion helps raise the temperature of the gas. The neutrinos, on the other hand, don't heat the gas. Neutrinos are particles that almost never interact with other particles. The average neutrino could pass unhindered through a lead wall a light-year thick. Consequently, the neutrinos do not warm the gas but race out of the sun at nearly the speed of light, carrying away roughly 2 percent of the energy produced.

■ **Figure 8-9**

The proton–proton chain combines four protons (at far left) to produce one helium nucleus (at right). Energy is produced mostly as gamma rays and as positrons, which combine with electrons and convert their mass into energy. Neutrinos escape, carrying away about 2 percent of the energy produced.



Creating one helium nucleus makes only a small amount of energy, hardly enough to raise a housefly one-thousandth of an inch. Because one reaction produces such a small amount of energy, it is obvious that many reactions are necessary to supply the energy needs of a star. The sun, for example, completes 10^{38} reactions per second, transforming 5 million tons of matter into energy every second. It might sound as if the sun is losing mass at a furious rate, but in its entire 10-billion-year lifetime, the sun will convert less than 0.07 percent of its mass into energy.

It is a **Common Misconception** that nuclear fusion in the sun is tremendously powerful. After all, the fusion of a milligram of hydrogen (roughly the mass of a match head) produces as much energy as burning 30 gallons of gasoline. However, at any one time, only a tiny fraction of the hydrogen atoms are fusing into helium, and the nuclear reactions in the sun are spread through a large volume in its core. Any single gram of matter produces only a little energy. A person of normal mass eating a normal diet produces about 4000 times more heat per gram than the matter in the core of the sun. Gram for gram, you are a much better heat producer than the sun. The sun produces a lot of energy because it contains a lot of grams of matter in its core.

Fusion reactions can occur only when the nuclei of two atoms get very close to each other. Because atomic nuclei carry positive charges, they repel each other with an electrostatic force called the Coulomb force. Physicists commonly refer to this repulsion between nuclei as the **Coulomb barrier**. To overcome this barrier and get close together, atomic nuclei must collide violently. Sufficiently violent collisions are rare unless the gas is very hot, in which case the nuclei move at high enough speeds. (Remember, an object's temperature is related to the speed with which its particles move.)

Nevertheless, the fusion of two protons is a highly unlikely process. If you could follow a single proton in the sun's core, you would see it encountering and bouncing off other protons millions of times a second, but you would have to follow it around for roughly a billion years before it happened to penetrate the Coulomb barrier and combine with another proton.

Because of the dependence of nuclear reactions on particle collisions, the reactions in the sun take place only near the center, where the gas is hot and dense. A high temperature ensures that collisions between nuclei are violent, and a high density ensures that there are enough collisions, and thus enough reactions, to make energy at the sun's rate.

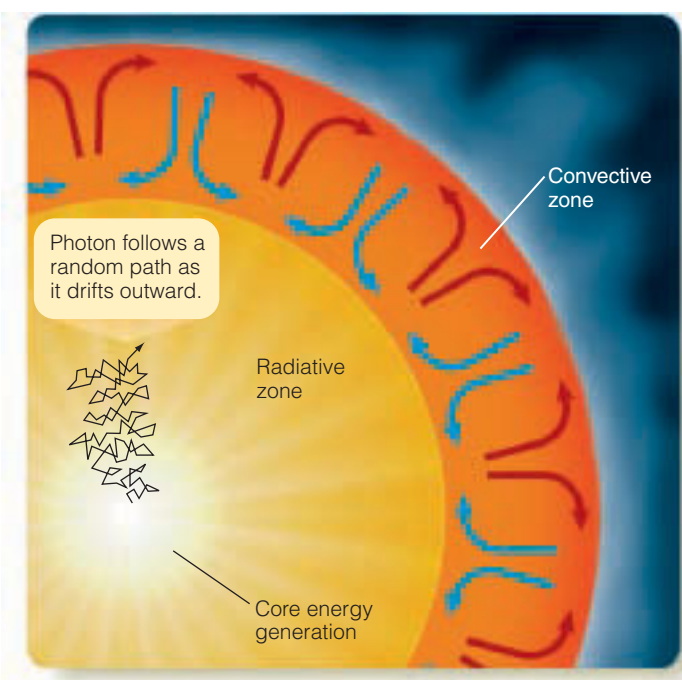
Energy Transport in the Sun

Now you are ready to follow the energy from the core of the sun to the surface. You will learn in a later chapter that astronomers have computed models indicating that the temperature at the center of the sun is about 15 million K. Compared with that, the sun's surface is very cool, only about 5800 K, so energy must flow from the high temperature core outward to the cooler surface where it is radiated into space.

Because the core is so hot, the photons bouncing around there are gamma rays. Each time a gamma ray encounters an electron, it is deflected or scattered in a random direction, and, as it bounces around, it slowly drifts outward toward the surface. That carries energy outward in the form of radiation, so astronomers refer to the inner parts of the sun as a **radiative zone**.

To examine this process, imagine picking a single gamma ray and following it to the surface. As your gamma ray is scattered over and over by the hot gas, it drifts outward into cooler layers, where the cooler gas tends to emit photons of longer wavelength. Your gamma ray will eventually be absorbed by the gas and reemitted as two X-rays. Now you must follow those two X-rays as they bounce around, and soon you will see them drifting outward into even cooler gas, where they will become a number of longer-wavelength photons.

The packet of energy you have been following, now represented by many photons, eventually reaches the outer layers of the sun, where the gas is so cool that it is not very transparent to radiation. There, energy backs up like water behind a dam, and the gas begins to churn in convection. Hot blobs of gas rise, and cool blobs sink. In this region, known as a **convective zone**, your packet of energy is carried outward not as photons but as circulating gas (■ Figure 8-10). Rising hot gas carries energy outward, of course, but sinking cool gas is a necessary part of the cycle that results in the net transport of energy outward.



■ **Figure 8-10**

A cross-section of the sun. Near the center, nuclear fusion reactions generate high temperatures. Energy flows outward through the radiative zone as photons are randomly deflected over and over by electrons. In the cooler, more opaque outer layers, the energy is carried by rising convection currents of hot gas (red arrows) and sinking currents of cooler gas (blue arrows).

Scientific Confidence

How can scientists be certain of something?

Sometimes scientists stick so firmly to their ideas in the face of contradictory claims that it sounds as if they are stubbornly refusing to consider alternatives. To see why they do this, consider the perpetual motion machine, a device that supposedly runs continuously with no source of energy. If you could invest in a real perpetual motion machine, you could sell cars that would run without any fuel. That's good mileage.

For centuries people have claimed to have invented perpetual motion machines, and for just as long scientists have been dismissing these claims as impossible. The problem with a perpetual motion machine is that it violates the law of conservation of energy, and scientists are not willing to accept that the law could be wrong. In fact, the Royal Academy of Sciences in Paris was so sure that a perpetual motion machine was impossible, and so tired of debunking hoaxes, that in 1775 they issued a formal statement refusing to deal with them. The U.S. Patent Office is so skeptical that they won't even consider granting a patent for one without seeing a working model first. Why do scientists seem so stubborn and close-minded on this issue?

Why isn't one person's belief in perpetual motion just as valid as another person's belief

in the law of conservation of energy? In fact, the two positions are not equally valid. The confidence physicists have in their law is not a belief or even an opinion; it is an understanding founded on the fact that the law has been tested uncountable times and has never failed. The law is a fundamental truth about nature and can be used to understand what is possible and what is impossible. In contrast, no one has ever successfully demonstrated a perpetual motion machine.

When the first observations of solar neutrinos detected fewer than were predicted, some scientists speculated that astronomers misunderstood how the sun makes its energy or that they misunderstood the internal structure of the sun. But many astronomers stubbornly refused to reject their model because the nuclear physics of the proton-proton chain is well understood, and models of the sun's structure have been tested successfully many times. The confidence astronomers felt in their understanding of the sun was an example of scientific certainty, and that confidence in basic natural laws prevented them from abandoning decades of work in the face of a single contradictory observation.



For centuries, people have tried to design a perpetual motion machine, but not a single one has ever worked. Scientists understand why.

What seems to be stubbornness among scientists is really their confidence in basic principles that have been tested over and over. Those principles are the keel that keeps the ship of science from rocking before every little breeze. Without even looking at that perpetual motion machine, your physicist friends can warn you not to invest.

It can take a million years for the energy from a single gamma ray to work its way outward first as radiation and then as convection. When the energy finally reaches the photosphere, it is radiated into space as about 1800 photons of visible light.

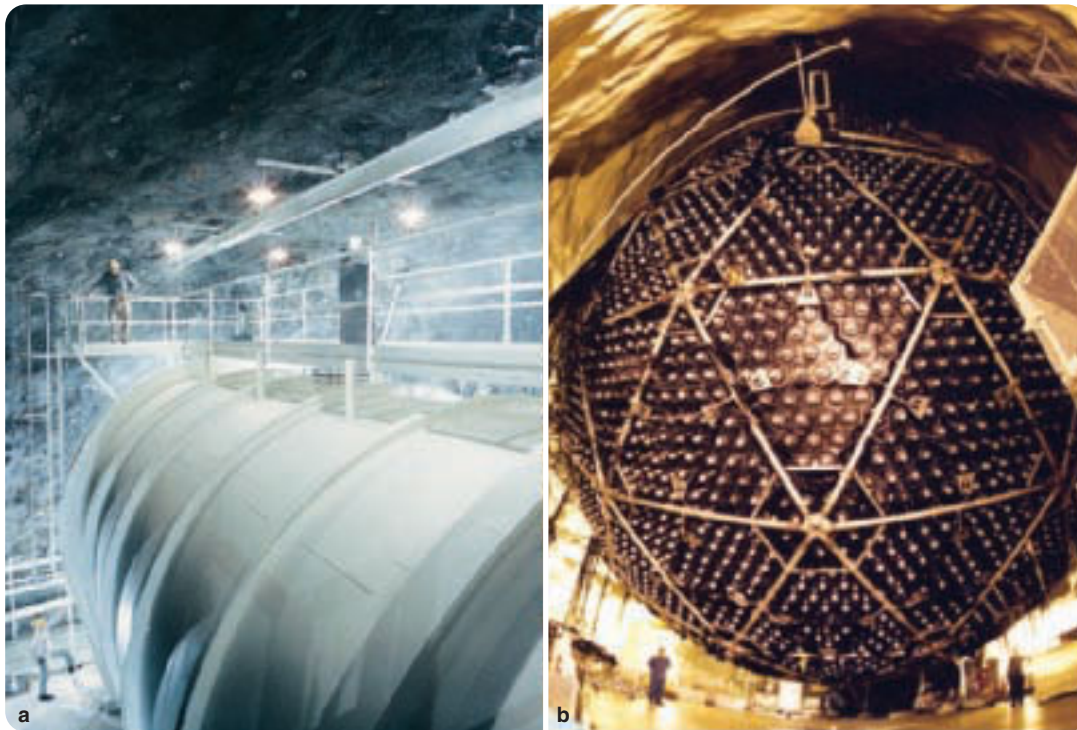
It is time to ask the critical question that lies at the heart of science. What is the evidence to support this theoretical explanation of how the sun makes its energy?

Counting Solar Neutrinos

Nuclear reactions in the sun's core produce floods of neutrinos that rush out of the sun and off into space. Over 10^{12} solar neutrinos flow through your body every second, but you never feel them because you are almost perfectly transparent to neutrinos. If you could detect these neutrinos, you could probe the sun's interior. You can't focus neutrinos with a lens or mirror, and they zip right through detectors used to count other atomic particles, but neutrinos of certain energies can trigger the radioactive decay of certain atoms. That gives astronomers a way to count solar neutrinos.

In the 1960s, chemist Raymond Davis Jr. devised a way to count neutrinos produced by hydrogen fusion in the sun. He buried a 100,000-gallon tank of cleaning fluid (perchloroethylene, C_2Cl_4) in the bottom of a South Dakota gold mine where cosmic rays could not reach it (■ Figure 8-11a) and counted the number of times a neutrino triggered a chlorine atom into becoming an argon atom. He expected to detect one neutrino a day, but he actually counted one-third as many as expected, only one every three days.

The Davis neutrino experiment created a huge controversy. Were scientists wrong about nuclear fusion in the sun? Did they misunderstand how neutrinos behave? Was the detector not working properly? Because astronomers had great confidence in their understanding of the solar interior, they didn't abandon their theories immediately (**How Do We Know? 8-1**). It took over 30 years, but eventually physicists were able to build better detectors, and they discovered that neutrinos oscillate among three different types, which physicists call flavors. Nuclear reactions in



■ **Figure 8-11**

(a) The Davis solar neutrino experiment used cleaning fluid and could detect only one of the three flavors of neutrinos. (Brookhaven National Laboratory) (b) The Sudbury Neutrino Observatory is a 12-meter-diameter globe containing water rich in deuterium (heavy hydrogen) in place of ordinary hydrogen. Buried 2100 m (6800 ft) deep in an Ontario mine, it can detect all three flavors of neutrinos and confirms that neutrinos oscillate. (Photo courtesy of SNO)

the sun produce only one flavor, and the Davis experiment was designed to detect (taste) that flavor. But during the 8-minute journey from the sun's core to Earth, the neutrinos oscillated so much that they were evenly distributed among the three different flavors by the time they arrived at Earth. That's why the Davis experiment detected only one-third of the number predicted.

The missing neutrinos have been detected by more sophisticated detectors (Figure 8-11b). In 2007, scientists announced that a supersensitive experiment in a tunnel under the Italian Alps had detected 50 neutrinos a day coming from the sun. The neutrinos have lower energies than those caught by the Davis experiment and are produced by a side reaction that produces beryllium-7. The number of neutrinos detected matches the prediction of models of nuclear fusion in the sun.

The center of the sun seems forever beyond human experience, but counting solar neutrinos provides evidence to confirm the theories. The sun makes its energy through nuclear fusion.

SCIENTIFIC ARGUMENT

Why does nuclear fusion require that the gas be very hot?

This argument has to include the basic physics of atoms and thermal energy. Inside a star, the gas is so hot it is ionized, which means the electrons have been stripped off the atoms leaving bare, positively charged nuclei. In the case of hydrogen, the nuclei are single protons. These atomic nuclei repel each other because of their positive charges, so they must collide with each other at high

velocity if they are to overcome that repulsion and get close enough together to fuse. If the atoms in a gas are moving rapidly, then the gas must have a high temperature, so nuclear fusion requires that the gas be very hot. If the gas is cooler than about 4 million K, hydrogen can't fuse because the protons don't collide violently enough to overcome the repulsion of their positive charges.

It is easy to see why nuclear fusion in the sun requires high temperature, but now expand your argument. **Why does it require high density?**

8-3 Solar Activity

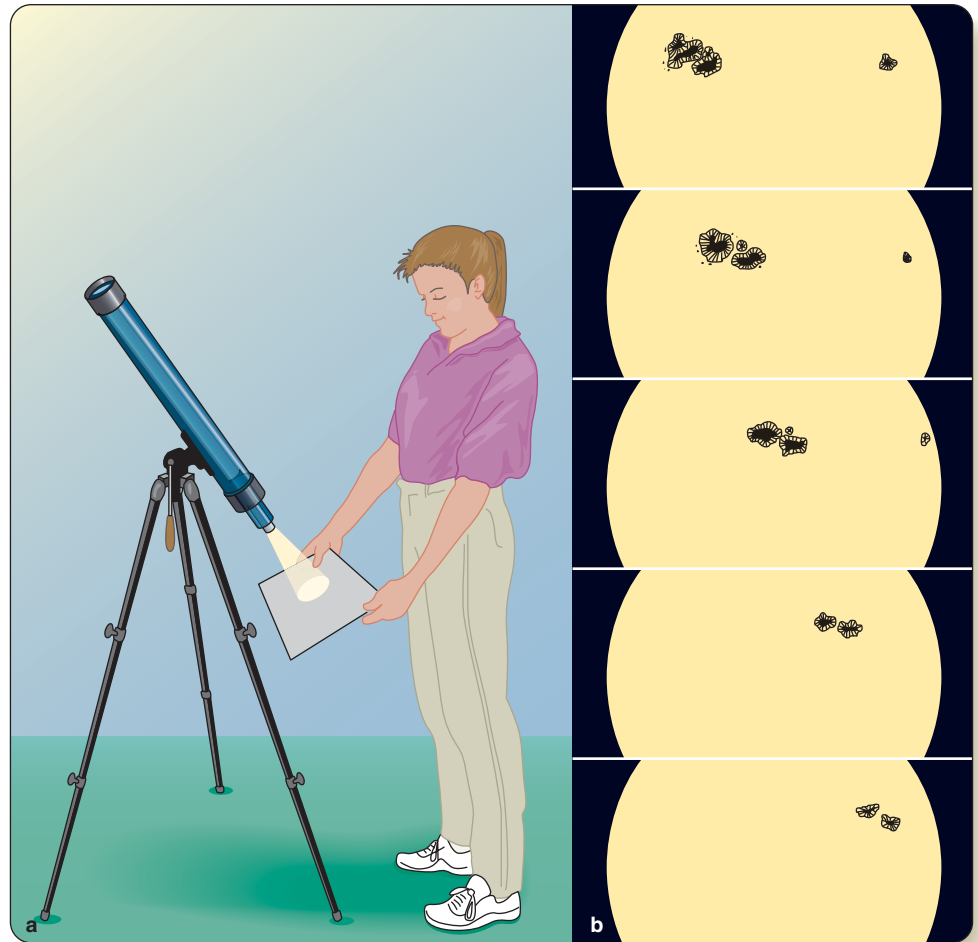
THE SUN IS NOT QUIET. It is home to slowly changing spots larger than Earth and vast eruptions that dwarf human imagination. All of these seemingly different forms of solar activity have one thing in common—magnetic fields. The weather on the sun is magnetic.

Observing the Sun

Solar activity is often visible with even a small telescope, but you should be very careful if you try to observe the sun. Sunlight is intense, and when it enters your eye it is absorbed and converted into thermal energy. The infrared radiation in sunlight is especially dangerous because your eyes can't detect it. You don't sense how intense the infrared is, but it is converted to thermal energy in your eyes and can burn and scar your retinas.

■ **Figure 8-12**

(a) Looking through a telescope at the sun is dangerous, but you can always view the sun safely with a small telescope by projecting its image on a white screen. (b) If you sketch the location and structure of sunspots on successive days, you will see the rotation of the sun and gradual changes in the size and structure of sunspots, just as Galileo did in 1610.



It is not safe to look directly at the sun, and it is even more dangerous to look at the sun through any optical instrument such as a telescope, binoculars, or even the viewfinder of a camera. The light-gathering power of such an optical system concentrates the sunlight and can cause severe injury. Never look at the sun with any optical instrument unless you are certain it is safe. ■ Figure 8-12a shows a safe way to observe the sun with a small telescope.

In the early 17th century, Galileo observed the sun and saw spots on its surface; day by day he saw the spots moving across the sun's disk. He rightly concluded that the sun was a sphere and was rotating. If you repeated his observations, you would probably also detect sunspots, a view that would look something like Figure 8-12b.

Sunspots

The dark sunspots that you see at visible wavelengths only hint at the complex processes that go on in the sun's atmosphere. To explore those processes, you must analyze images and spectra at a wide range of wavelengths.

Study **Sunspots and the Sunspot Cycle** on pages 156–157 and notice five important points and four new terms:

- 1 Sunspots are cool spots on the sun's surface caused by strong magnetic fields.
- 2 Sunspots follow an 11-year cycle, becoming more numerous, reaching a maximum, and then becoming much less numerous. The *Maunder butterfly diagram* shows how the location of sunspots changes during a cycle.
- 3 The *Zeeman effect* gives astronomers a way to measure the strength of magnetic fields on the sun and provide evidence that sunspots contain strong magnetic fields.
- 4 The intensity of the sunspot cycle can vary from cycle to cycle and appears to have almost faded away during the *Maunder minimum* in the late 17th century. That seems to have affected Earth's climate.
- 5 The evidence is clear that sunspots are part of *active regions* dominated by magnetic fields that involve all layers of the sun's atmosphere.

The sunspot groups are merely the visible traces of magnetically active regions. But what causes this magnetic activity? The answer is linked to the growth and decay cycle of the sun's overall magnetic field.

Sunspots and the Sunspot Cycle

1 The dark spots that appear on the sun are only the visible traces of complex regions of activity. Observations over many years and at a range of wavelengths tell you that sunspots are clearly linked to the sun's magnetic field.

Spectra show that sunspots are cooler than the photosphere with a temperature of about 4200 K. The photosphere has a temperature of about 5800 K. Because the total amount of energy radiated by a surface depends on its temperature raised to the fourth power, sunspots look dark in comparison. Actually, a sunspot emits quite a bit of radiation. If the sun were removed and only an average-size sunspot were left behind, it would be brighter than the full moon.

Visual wavelength image

Umbra

Penumbra

A typical sunspot is about twice the size of Earth, but there is a wide range of sizes. They appear, last a few weeks to as long as 2 months, and then shrink away. Usually, sunspots occur in pairs or complex groups.



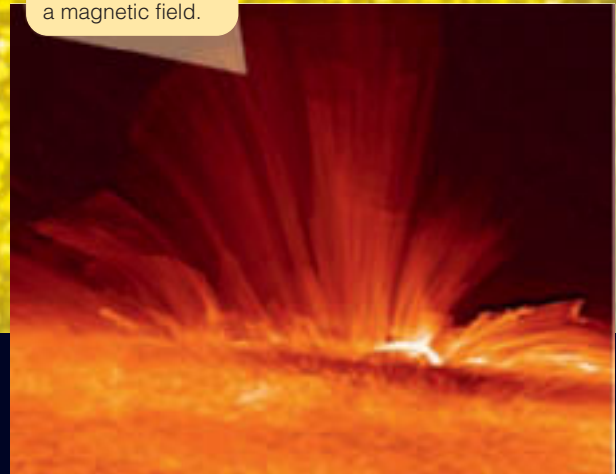
Earth to scale

NASA

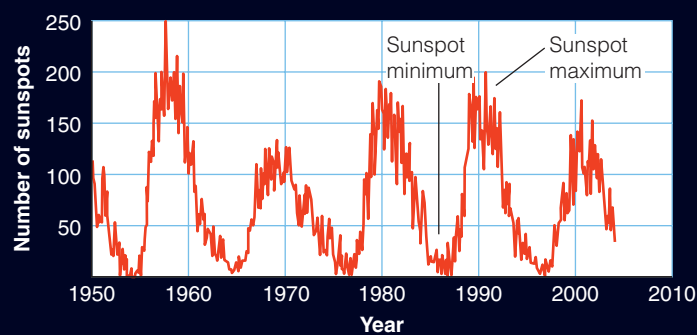
Sunspots are not shadows, but astronomers refer to the dark core of a sunspot as its umbra and the outer, lighter region as the penumbra.

Hinode JAXA/NASA

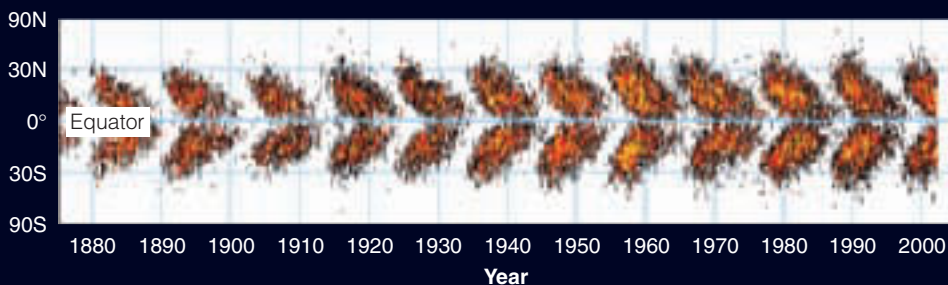
Streamers above a sunspot suggest a magnetic field.



Hinode JAXA/NASA



2 The number of spots visible on the sun varies in a cycle with a period of 11 years. At maximum, there are often over 100 spots visible. At minimum, there are very few.



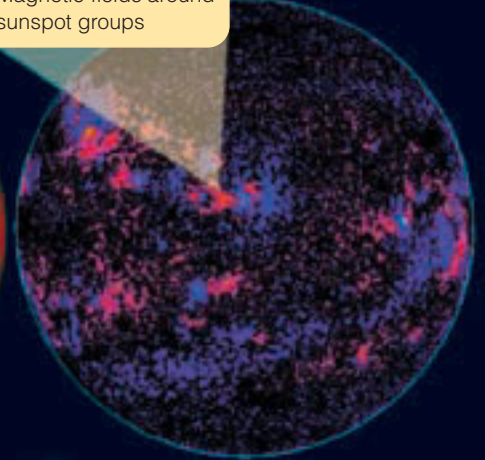
2a Early in the cycle, spots appear at high latitudes north and south of the sun's equator. Later in the cycle, the spots appear closer to the sun's equator. If you plot the latitude of sunspots versus time, the graph looks like butterfly wings, as shown in this **Maunder butterfly diagram**, named after E. Walter Maunder of Greenwich Observatory.

3

Astronomers can measure magnetic fields on the sun using the **Zeeman effect** as shown below. When an atom is in a magnetic field, the electron orbits are altered, and the atom is able to absorb a number of different wavelength photons even though it was originally limited to a single wavelength. In the spectrum, you see single lines split into multiple components, with the separation between the components proportional to the strength of the magnetic field.

Sunspot groups

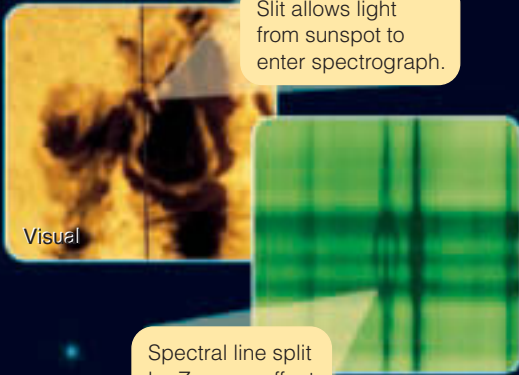
Magnetic fields around sunspot groups



Ultraviolet filtergram

Magnetic image

Simultaneous images

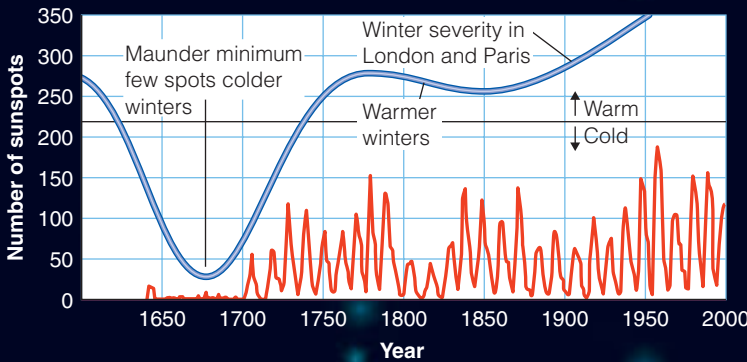


Slit allows light from sunspot to enter spectrograph.

Spectral line split by Zeeman effect

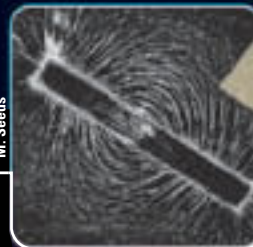
3a

Images of the sun above show that sunspots contain magnetic fields a few thousand times stronger than Earth's. The strong fields are believed to inhibit gas motion below the photosphere; consequently, convection is reduced below the sunspot, and the surface there is cooler. Heat prevented from emerging through the sunspot is deflected and emerges around the sunspot, which can be detected in ultraviolet and infrared images.



4

Historical records show that there were very few sunspots from about 1645 to 1715, a phenomenon known as the **Maunder minimum**. This coincides with a period called the "little ice age," a period of unusually cool weather in Europe and North America from about 1500 to about 1850, as shown in the graph at left. Other such periods of cooler climate are known. The evidence suggests that there is a link between solar activity and the amount of solar energy Earth receives. This link has been confirmed by measurements made by spacecraft above Earth's atmosphere.



Magnetic fields can reveal themselves by their shape. For example, iron filings sprinkled over a bar magnet reveal an arched shape.

The complexity of an active region becomes visible at short wavelengths.

Far-UV image

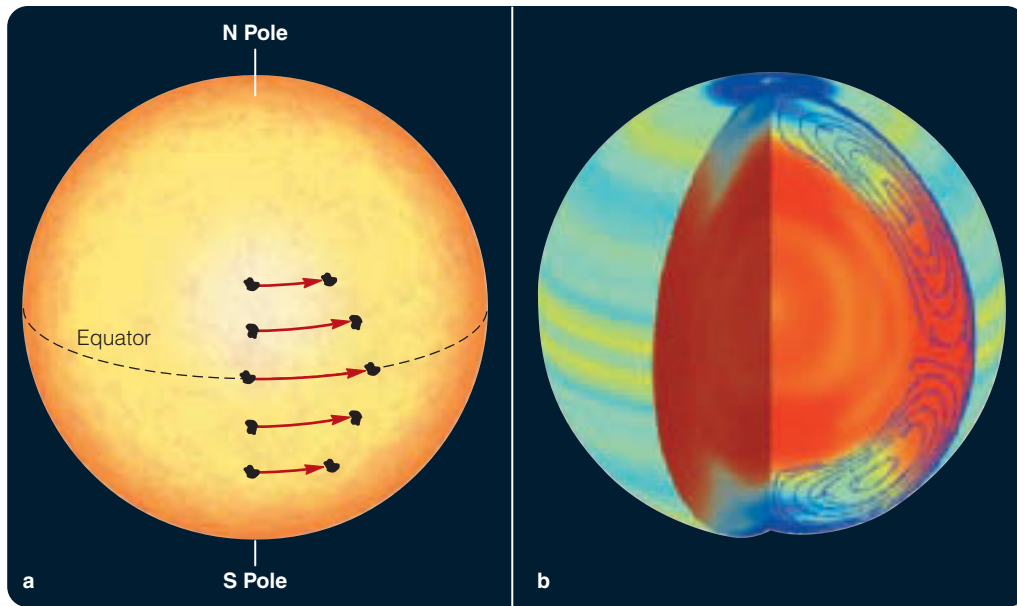
5

Observations at nonvisible wavelengths reveal that the chromosphere and corona above sunspots are violently disturbed in what astronomers call **active regions**. Spectrographic observations show that active regions contain powerful magnetic fields. Arched structures above an active region are evidence of gas trapped in magnetic fields.

Visual-wavelength image

Simultaneous images

Far-UV image



■ **Figure 8-13**

(a) In general, the photosphere of the sun rotates faster at the equator than at higher latitudes. If you started five sunspots in a row, they would not stay lined up as the sun rotates. (b) Detailed analysis of the sun's rotation from helioseismology reveals regions of slow rotation (blue) and rapid rotation (red). Such studies show that the interior of the sun rotates differentially and that currents similar to the trade winds in Earth's atmosphere flow through the sun. (NASA/SOI)

The Sun's Magnetic Cycle

The sun's magnetic field is powered by the energy flowing outward through the moving currents of gas. The gas is highly ionized, so it is a very good conductor of electricity. When an electrical conductor rotates and is stirred by convection, it can convert some of the energy flowing outward as convection into a magnetic field. This process is called the **dynamo effect**, and it is understood also to operate in Earth's core and produce Earth's magnetic field. Helioseismologists have found evidence that the dynamo effect generates the sun's magnetic field at the bottom of the convection zone deep under the photosphere.

The sun's magnetic field cannot be as stable as Earth's. The sun does not rotate as a rigid body. It is a gas from its outermost layers down to its center, so some parts of the sun can rotate faster than other parts. The equatorial region of the photosphere rotates faster than do regions at higher latitudes (■ Figure 8-13a). At the equator, the photosphere rotates once every 25 days, but at latitude 45° one rotation takes 27.8 days. Helioseismology can map the rotation throughout the interior (Figure 8-13b) and has found that different levels in the sun rotate with different periods. This phenomenon is called **differential rotation**, and it is clearly linked with the magnetic cycle.

Although the magnetic cycle is not fully understood, the **Babcock model** (named for its inventor) explains the magnetic cycle as a progressive tangling of the solar magnetic field. Because the electrons in an ionized gas are free to move, the gas is a very good conductor of electricity, so any magnetic field in the gas is "frozen" into it. If the gas moves, the magnetic field must move with it. Differential rotation drags the magnetic field along and wraps it around the sun like a long string caught on a turning

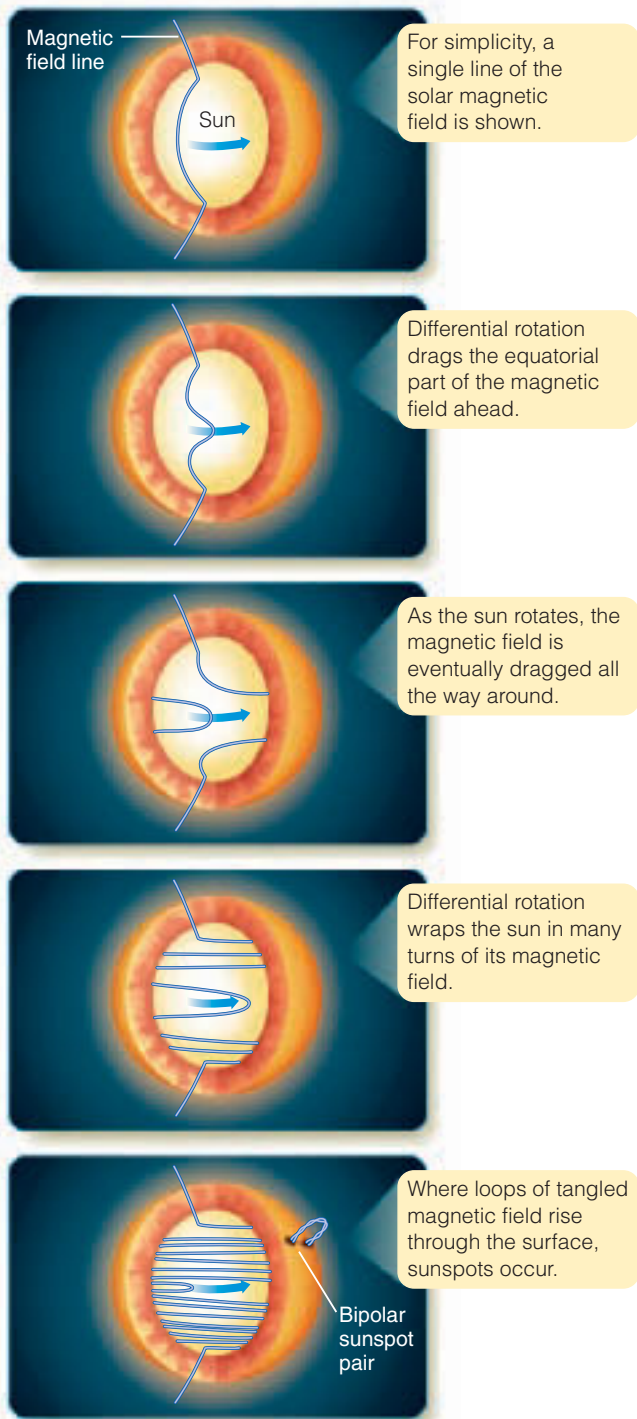
hubcap. Rising and sinking gas currents twist the field into rope-like tubes, which tend to float upward. The model predicts that sunspot pairs occur where these magnetic tubes burst through the sun's surface (■ Figure 8-14).

Sunspots tend to occur in groups or pairs, and the magnetic field around the pair resembles that around a bar magnet with one end magnetic north and the other end magnetic south, just as you would expect if a magnetic tube emerged through one sunspot in a pair and reentered through the other. At any one time, sunspot pairs south of the sun's equator have reversed polarity compared with those north of the sun's equator. ■ Figure 8-15 illustrates this by showing sunspot pairs south of the sun's equator moving with magnetic south poles leading, and sunspots north of the sun's equator moving with magnetic north poles leading. At the end of an 11-year sunspot cycle, the new spots appear with reversed magnetic polarity.

The Babcock model accounts for the reversal of the sun's magnetic field from cycle to cycle. As the magnetic field becomes tangled, adjacent regions of the sun are dominated by magnetic fields that point in different directions. After about 11 years of tangling, the field becomes so complex that adjacent regions of the sun begin changing their magnetic field to agree with neighboring regions. The entire field quickly rearranges itself into a simpler pattern, and differential rotation begins winding it up to start a new cycle. But the newly organized field is reversed, and the next sunspot cycle begins with magnetic north replaced by magnetic south. Consequently, the complete magnetic cycle is 22 years long, and the sunspot cycle is 11 years long.

This magnetic cycle also explains the Maunder butterfly diagram. As a sunspot cycle begins, the twisted tubes of magnetic force first begin to float upward and produce sunspot pairs at

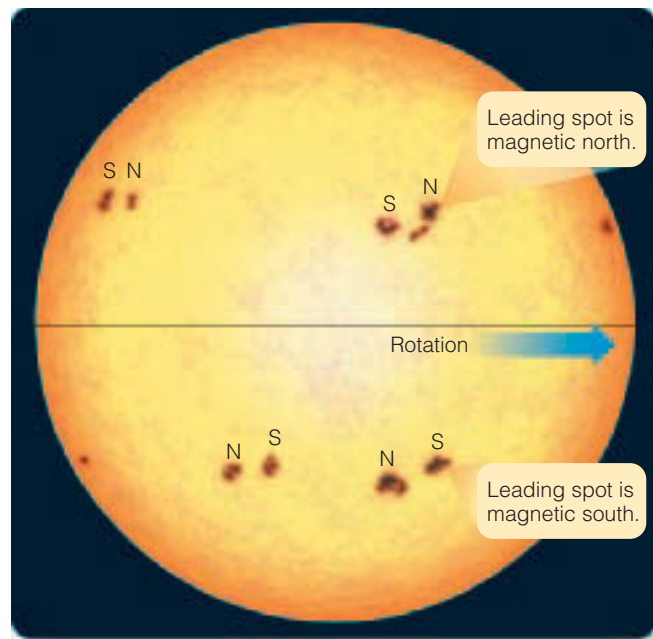
The Solar Magnetic Cycle



■ **Figure 8-14**

The Babcock model of the solar magnetic cycle explains the sunspot cycle as a consequence of the sun's differential rotation gradually winding up the magnetic field near the base of the sun's outer, convective layer.

higher latitudes on the sun. Consequently the first sunspots in a cycle appear farther north and south of the equator. Later in the cycle, when the field is more tightly wound, the tubes of



■ **Figure 8-15**

In sunspot groups, here simplified into pairs of major spots, the leading spot and the trailing spot have opposite magnetic polarity. Spot pairs in the southern hemisphere have reversed polarity from those in the northern hemisphere.

magnetic force arch up through the surface closer to the equator. As a result, the later sunspot pairs in a cycle appear closer to the equator.

Notice the power of a scientific model. The Babcock model may in fact be incorrect in some details, but it provides a framework around which to organize descriptions of complex solar activity. Even though the model of the sky in Chapter 2 and the model of the atom in Chapter 7 are only partially correct, they served as organizing themes to guide your thinking. Similarly, although the precise details of the solar magnetic cycle are not yet understood, the Babcock model gives you a general picture of the behavior of the sun's magnetic field (**How Do We Know? 8-2**).

Spots and Magnetic Cycles of Other Stars

The sun seems to be a representative star, so you should expect other stars to have similar cycles of starspots and magnetic fields. This is a difficult topic, because, except for the sun, the stars are so far away that no surface detail is visible. Some stars, however, vary in brightness in ways that suggest they are mottled by dark spots. As these stars rotate, their total brightnesses change slightly, depending on the number of spots on the side facing Earth. High-precision spectroscopic analysis has even allowed astronomers to map the locations of spots on the surfaces of

Confirmation and Consolidation

What do scientists do all day? The scientific method is sometimes portrayed as a kind of assembly line where scientists crank out new hypotheses and then test them through observation. In reality, scientists don't often generate entirely new hypotheses. It is rare that an astronomer makes an observation that disproves a long-held theory and triggers a revolution in science. Then what is the daily grind of science really about?

Many observations and experiments confirm already-tested hypotheses. The biologist knows that all worker bees in a hive are sisters because they are all female, and they all had the same mother, the queen bee. A biologist can study the DNA from many workers and confirm that hypothesis. By repeatedly confirming a hypothesis, scientists build confidence in the hypothesis and may be able to extend it. Do all of the workers in a hive have

the same father, or did the queen mate with more than one male drone?

Another aspect of routine science is consolidation, the linking of a hypothesis to other well-studied phenomena. A biologist can study yellow jacket wasps from a single nest and discover that the wasps, too, are sisters. There must be a queen wasp who lays all of the eggs in a nest. But in a few nests, the scientist may find two sets of unrelated sister workers. Those nests must contain two queens sharing the nest for convenience and protection. From his study of wasps, the biologist consolidates what he knows about bees with what others have learned about wasps and reveals something new: That bees and wasps have evolved in similar ways for similar reasons.

Confirmation and consolidation allow scientists to build confidence in their



A yellow jacket is a wasp from a nest containing a queen wasp. (Michael Dunham/Getty Images)

understanding and extend it to explain more about nature.

certain stars (■ Figure 8-16a). Such results confirm that the sunspots you see on our sun are not unusual.

Certain features found in stellar spectra are associated with magnetic fields. Regions of strong magnetic fields on the solar surface emit strongly at the central wavelengths of the two strongest lines of ionized calcium. This calcium emission appears in the spectra of other sun-like stars and suggests that these stars, too, have strong magnetic fields on their surfaces. In some cases, the strength of this calcium emission varies over periods of days or weeks and suggests that the stars have active regions and are rotating with periods similar to that of the sun. These stars presumably have sunspots (“starspots”) as well.

In 1966, astronomers began a long-term project that monitored the strengths of these calcium emission features in the spectra of 91 stars with temperatures ranging from 1000 K hotter than the sun to 3000 K cooler, considered most likely to have sun-like magnetic activity on their surfaces. The observations show that the strength of the calcium emission varies over periods of years. The calcium emission averaged over the sun's disk varies with the sunspot cycle, and similar periodic variations can be seen in the spectra of some of the stars studied (Figure 8-16b). The star 107 Piscium, for example, appears to have a starspot cycle lasting nine years. At least one star, tau Bootis, has been observed to reverse its magnetic field. This kind of evidence suggests that stars like the sun have similar magnetic cycles, and that the sun is normal in this respect.

Chromospheric and Coronal Activity

The solar magnetic fields extend high into the chromosphere and corona, where they produce beautiful and powerful phenomena. Study **Magnetic Solar Phenomena** on pages 162–163 and notice three important points and seven new terms:

- 1 All solar activity is magnetic. The arched shapes of *prominences* are produced by magnetic fields, and *filaments* are prominences seen from above.
- 2 Tremendous energy can be stored in arches of magnetic field, and when two arches encounter each other a *reconnection* can release powerful eruptions called *flares*. Although these eruptions occur far from Earth, they can affect us in dramatic ways, and *coronal mass ejections (CMEs)* can trigger communications blackouts and *auroras*.
- 3 In some regions of the solar surface, the magnetic field does not loop back. High-energy gas from these *coronal holes* flows outward and produces much of the solar wind.

You may have heard the **Common Misconception** that an auroral display in the night sky is caused by sunlight reflecting off of the ice and snow at Earth's North Pole. It is fun to think of polar bears standing on sunlit slabs of ice, but that doesn't cause auroras. You know that auroras are produced by gases in Earth's upper atmosphere excited to glowing by energy from the solar wind.

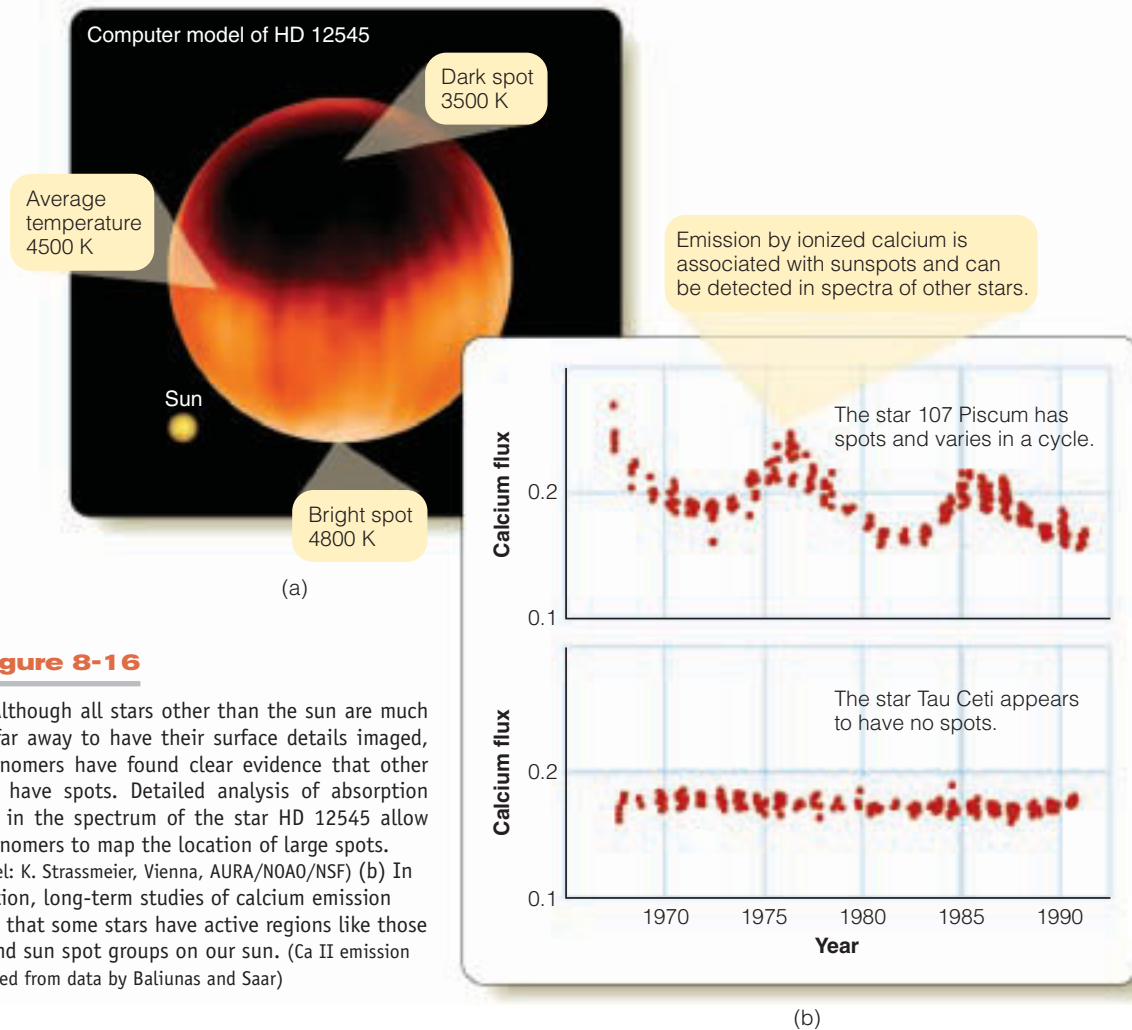


Figure 8-16

(a) Although all stars other than the sun are much too far away to have their surface details imaged, astronomers have found clear evidence that other stars have spots. Detailed analysis of absorption lines in the spectrum of the star HD 12545 allow astronomers to map the location of large spots. (Model: K. Strassmeier, Vienna, AURA/NOAO/NSF) (b) In addition, long-term studies of calcium emission show that some stars have active regions like those around sun spot groups on our sun. (Ca II emission adapted from data by Baliunas and Saar)

The Solar Constant

Even a small change in the sun's energy output could produce dramatic changes in Earth's climate. The continued existence of the human species depends on the constancy of the sun, but we humans know very little about the variation of the sun's energy output.

The energy production of the sun can be monitored by adding up all of the energy falling on 1 square meter of Earth's surface during 1 second. Of course, some correction for the absorption of Earth's atmosphere is necessary, and you must count all wavelengths from X-rays to radio waves. The result, which is called the **solar constant**, amounts to about 1360 joules per square meter per second. Is the sun really constant? A change in the solar constant of only 1 percent could change Earth's average temperature by about 1°C (roughly 2°F). This may not seem like much, but during the last ice age Earth's average temperature was only about 5°C cooler than it is now.

Some of the best measurements of the solar constant were made by instruments aboard the Solar Maximum Mission satellite. These have shown variations in the energy received from the

sun of about 0.1 percent that lasted for days or weeks. Superimposed on that random variation is a long-term decrease of about 0.018 percent per year that has been confirmed by observations made by sounding rockets, balloons, and satellites. This long-term decrease may be related to a cycle of activity on the sun with a period longer than the 22-year magnetic cycle.

Small, random fluctuations will not affect Earth's climate, but a long-term decrease over a decade or more could cause worldwide cooling. History contains some evidence that the solar constant may have varied in the past. As you saw on page 157, the "Little Ice Age" was a period of unusually cool weather in Europe and America that lasted from about 1500 to 1850.* The average temperature worldwide was about 1°C cooler than it is now. This period of cool weather corresponded to the Maunder minimum, a period of reduced solar activity—few sunspots, no auroral displays, and no solar coronas visible during solar eclipses.

*Ironically, the Maunder minimum coincides with the reign of Louis XIV of France, the "Sun King."

Magnetic Solar Phenomena

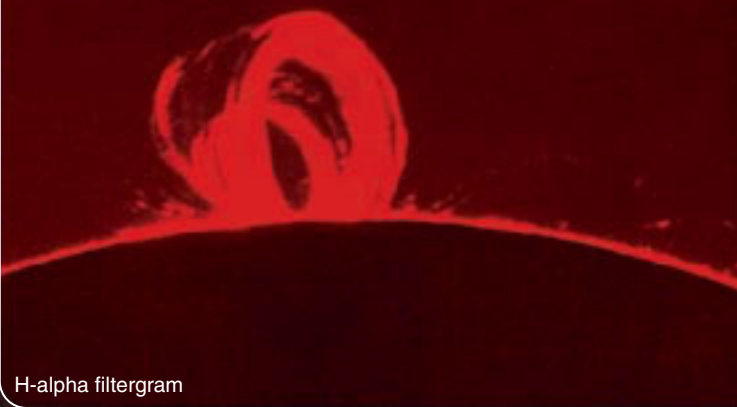
1 Magnetic phenomena in the chromosphere and corona, like magnetic weather, result as constantly changing magnetic fields on the sun trap ionized gas to produce beautiful arches and powerful outbursts. Some of this solar activity can affect Earth's magnetic field and atmosphere.

This ultraviolet image of the solar surface was made by the NASA TRACE spacecraft. It shows hot gas trapped in magnetic arches extending above active regions. At visual wavelengths, you would see sunspot groups in these active regions.

The gas in prominences may be 60,000 to 80,000 K, quite cold compared with the low-density gas in the corona, which may be as hot as a million Kelvin.

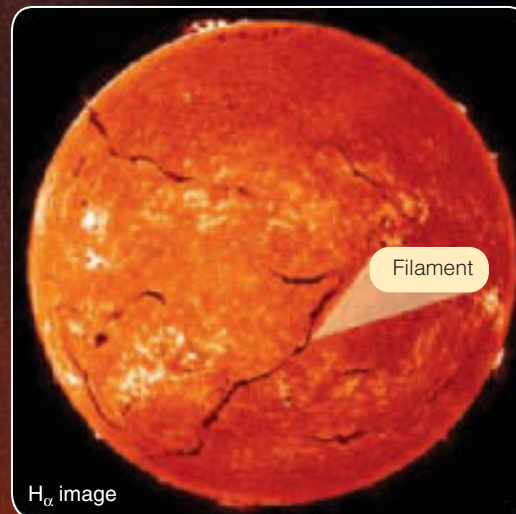
Trace/NASA

Sacramento Peak Observatory



H-alpha filtergram

1a A **prominence** is composed of ionized gas trapped in a magnetic arch rising up through the photosphere and chromosphere into the lower corona. Seen during total solar eclipses at the edge of the solar disk, prominences look pink because of the three Balmer emission lines. The image above shows the arch shape suggestive of magnetic fields. Seen from above against the sun's bright surface, prominences form dark **filaments**.



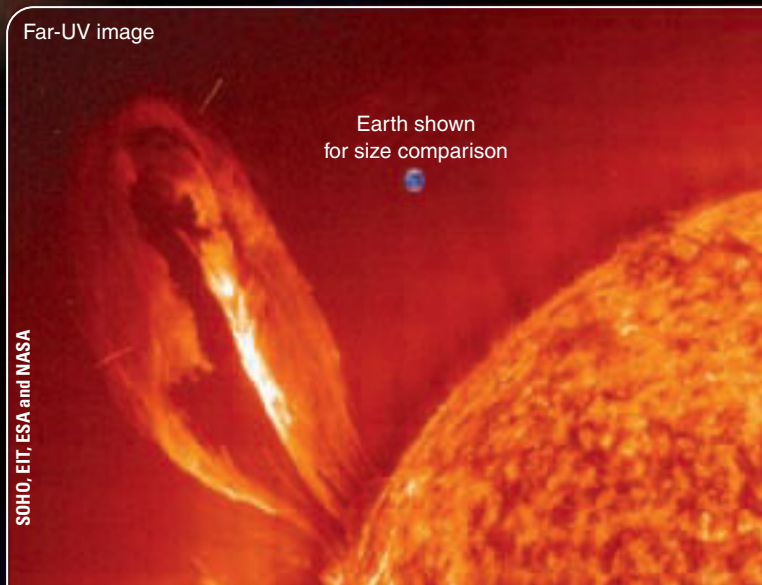
H_α image

NOAA/SEL/USAF

1b Quiescent prominences may hang in the lower corona for many days, whereas eruptive prominences burst upward in hours. The eruptive prominence below is many Earth diameters long.

Far-UV image

SOHO, EIT, ESA and NASA



Earth shown for size comparison

2

Solar **flares** rise to maximum in minutes and decay in an hour. They occur in active regions where oppositely directed magnetic fields meet and cancel each other out in what astronomers call **reconnections**. Energy stored in the magnetic fields is released as short-wavelength photons and as high-energy protons and electrons. X-ray and ultraviolet photons reach Earth in 8 minutes and increase ionization in our atmosphere, which can interfere with radio communications. Particles from flares reach Earth hours or days later as gusts in the solar wind, which can distort Earth's magnetic field and disrupt navigation systems. Solar flares can also cause surges in electrical power lines and damage to Earth satellites.

2a

At right, waves rush outward at 50 km/sec from the site of a solar flare 40,000 times stronger than the 1906 San Francisco earthquake. The biggest solar flares can be a billion times more powerful than a hydrogen bomb.

2b

The solar wind, enhanced by eruptions on the sun, interacts with Earth's magnetic field and can create electrical currents up to a million megawatts. Those currents flowing down into a ring around Earth's magnetic poles excite atoms in Earth's upper atmosphere to emit photons as shown below. Seen from Earth's surface, the gas produces glowing clouds and curtains of **aurora**.

Coronal mass ejection

Ring of aurora around the north magnetic pole

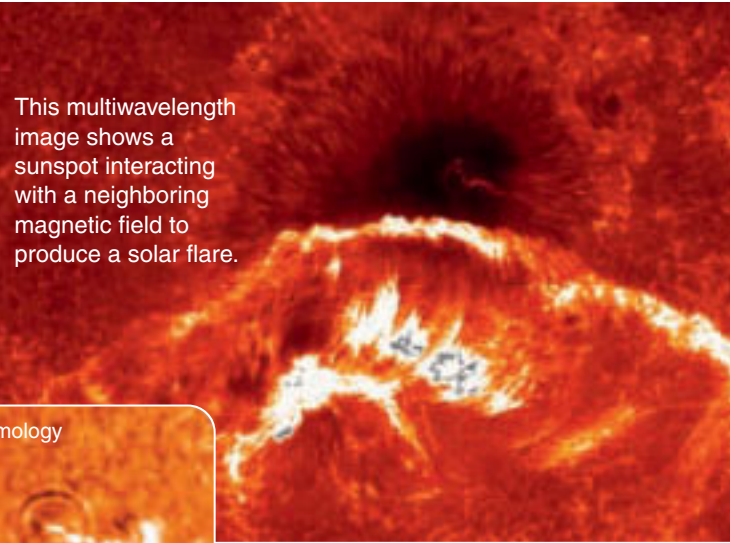
NSSDC, Holzworth and Meng

2c

Magnetic reconnections can release enough energy to blow large amounts of ionized gas outward from the corona in **coronal mass ejections (CMEs)**. If a CME strikes Earth, it can produce especially violent disturbances in Earth's magnetic field.

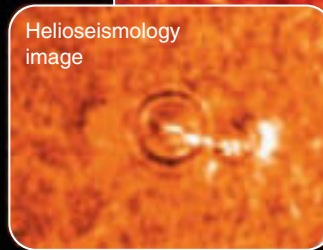
3

Much of the solar wind comes from **coronal holes**, where the magnetic field does not loop back into the sun. These open magnetic fields allow ionized gas in the corona to flow away as the solar wind. The dark area in this X-ray image at right is a coronal hole.



This multiwavelength image shows a sunspot interacting with a neighboring magnetic field to produce a solar flare.

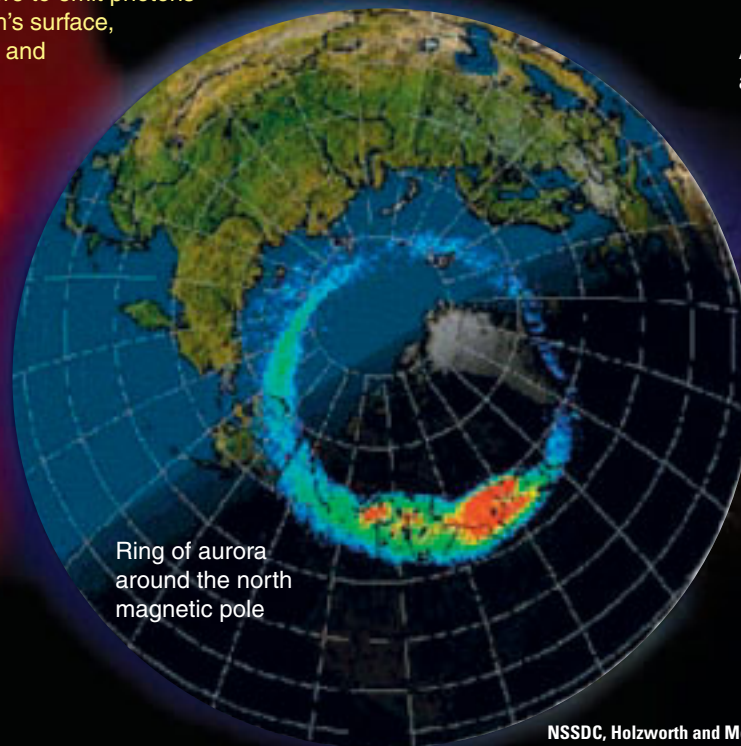
Hinode JAXA/NASA



Helioseismology image

SOHO/MDI, ESA, and NASA

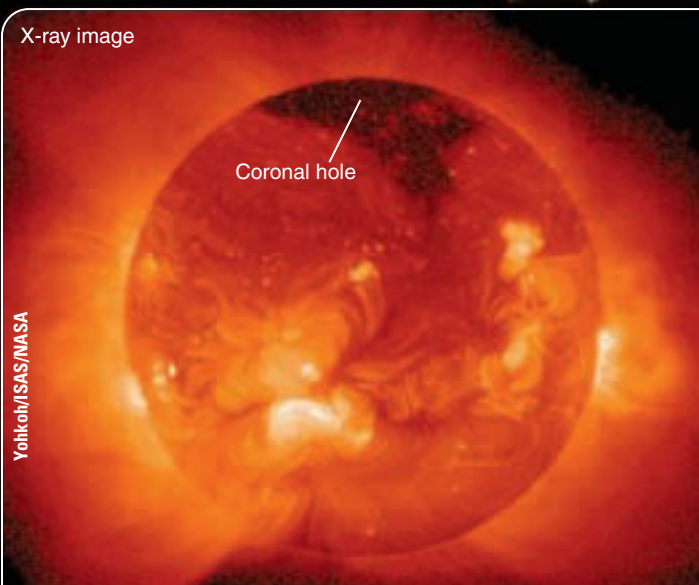
Auroras occur about 130 km above the Earth's surface.



X-ray image

Coronal hole

Yohkoh/ISAS/NASA



In contrast, an earlier period called the Grand Maximum, lasting from about AD 1100 to about 1250, saw a warming of Earth's climate. The Vikings were able to explore and colonize Greenland, and native communities in parts of North America were forced to abandon their settlements because of long droughts. The Grand Maximum may have been caused by a small change in solar activity, but the evidence is not conclusive.

Other minima and maxima have been found in climate data taken from studies of the growth rings of trees. In good years, trees add a thicker growth ring than in poor years, so measuring tree rings can reveal the climate in the past. Evidently, solar activity can increase or decrease the solar constant very slightly and affect Earth's climate in dramatic ways. The future of our civilization on Earth may depend on our learning to understand the solar constant.

SCIENTIFIC ARGUMENT

What kind of activity would the sun have if it didn't rotate differentially?

Once again, it can help you understand a concept by constructing an argument with one factor changed. Begin by thinking about the Babcock model. If the sun didn't rotate differentially, its equator traveling faster than its higher latitudes, then the magnetic field might not get wound up, and there might not be a solar cycle. Twisted tubes of magnetic field might not form and rise through the photosphere to produce prominences and flares, although convection might tangle the magnetic field slightly and produce some activity. Is the magnetic activity that heats the chromosphere and corona driven by differential rotation or by convection? It is hard to guess; but, without differential rotation, the sun might not have a strong magnetic field and high-temperature gas above its photosphere.

This is very speculative, but speculating within a scientific argument can be revealing. For example, redo the argument above. **What do you think the sun would be like if it had no convection inside?**

What Are We? Sunlight

We live very close to a star and depend on it for survival. All of our food comes from sunlight that was captured by plants on land or by plankton in the oceans. We either eat those plants directly or eat the animals that feed on those plants. Whether you had salad, seafood, or a cheeseburger for supper last night, you dined on sunlight, thanks to photosynthesis.

Almost all of the energy that powers human civilization came from the sun

through photosynthesis in ancient plants that were buried and converted to coal, oil, and natural gas. New technology is making energy from plant products like corn, soy beans, and sugar. It is all stored sunlight. Windmills generate electrical power, and the wind blows because of heat from the sun. Photocells make electricity directly from sunlight. Even our bodies have adapted to use sunlight to manufacture vitamin D.

Our planet is warmed by the sun, and without that warmth the oceans would be ice and much of the atmosphere would be a coating of frost. Books often refer to the sun as "our sun" or "our star." It is ours in the sense that we live beside it and by its light and warmth, but we can hardly say it belongs to us. It is better to say that we belong to the sun.

Study and Review

Summary

- ▶ The sun is very bright, and its light and infrared radiation can burn your eyes, so you must take great care in observing it. At sunset or sunrise when it is safe to look at the sun, you see the sun's photosphere, the level in the sun from which visible photons most easily escape. Dark **sunspots (p. 143)** come and go on the sun, but only rarely are they large enough to be visible to the unaided eye.
- ▶ The solar atmosphere consists of three layers of hot, low-density gas: the photosphere, chromosphere, and corona.
- ▶ The **granulation (p. 144)** of the photosphere is produced by **convection (p. 145)** currents of hot gas rising from below. Larger

supergranules (p. 145) appear to be caused by larger convection currents deeper in the sun.

- ▶ The edge or **limb (p. 145)** of the solar disk is dimmer than the center. This **limb darkening (p. 145)** is evidence that the temperature in the solar atmosphere increases with depth.
- ▶ The chromosphere is most easily visible during total solar eclipses, when it flashes into view for a few seconds. It is a thin, hot layer of gas just above the photosphere, and its pink color is caused by the Balmer emission lines in its spectrum.
- ▶ **Filtergrams (p. 146)** of the chromosphere reveal **spicules (p. 146)**, flamelike structures extending upward into the lower corona.

- ▶ The corona is the sun's outermost atmospheric layer and can be imaged using a **coronagraph (p. 146)**. It is composed of a very-low-density, very hot gas extending many solar radii from the visible sun. Its high temperature—over 2,000,000 K—is believed to be maintained by the magnetic field extending up through the photosphere—the **magnetic carpet (p. 147)**—and by magnetic waves coming from below the photosphere.
- ▶ Parts of the corona give rise to the **solar wind (p. 147)**, a breeze of low-density ionized gas streaming away from the sun.
- ▶ Solar astronomers can study the motion, density, and temperature of gases inside the sun by analyzing the way the solar surface oscillates. Known as **helioseismology (p. 148)**, this field of study requires large amounts of data and extensive computer analysis.
- ▶ There are only four forces in nature: the electromagnetic force, the gravitational force, the **weak force (p. 150)**, and the **strong force (p. 150)**. In nuclear fission or nuclear fusion, the energy comes from the strong force. Physicists are working on unifying the four forces under one mathematical description.
- ▶ Nuclear reactors on Earth generate energy through **nuclear fission (p. 150)**, during which large nuclei such as uranium break into smaller fragments. The sun generates its energy through **nuclear fusion (p. 150)**, during which hydrogen nuclei fuse to produce helium nuclei.
- ▶ Hydrogen fusion in the sun proceeds in three steps known as the **proton–proton chain (p. 151)**. The first step in the chain combines two hydrogen nuclei to produce a heavy hydrogen nucleus called **deuterium (p. 151)**. The second step forms light helium, and the third step combines the light helium nuclei to form normal helium. Energy is released as **positrons (p. 151)**, **neutrinos (p. 151)**, gamma rays, and the rapid motion of particles flying away.
- ▶ Fusion can occur only at the center of the sun because charged particles repel each other, and high temperatures are needed to give particles high enough velocities to penetrate this **Coulomb barrier (p. 152)**. High densities are needed to provide large numbers of reactions.
- ▶ Neutrinos escape from the sun's core at nearly the speed of light, carrying away about 2 percent of the energy produced by fusion. Observations of fewer neutrinos than expected coming from the sun's core are now explained by the oscillation of neutrinos among three different types (flavors). The detection of solar neutrinos confirms the theory that the sun's energy comes from hydrogen fusion.
- ▶ Energy flows out of the sun's core as photons traveling through the **radiative zone (p. 152)** and closer to the surface as rising currents of hot gas and sinking currents of cooler gas in the **convective zone (p. 152)**.
- ▶ Sunspots seem dark because they are slightly cooler than the rest of the photosphere. The average sunspot is about twice the size of Earth. They appear for a month or so and then fade away, and the number of spots on the sun varies with an 11-year cycle.
- ▶ Early in a sunspot cycle, spots appear farther from the sun's equator, and later in the cycle they appear closer to the equator. This is shown in the **Maunder butterfly diagram (p. 155)**.
- ▶ Astronomers can use the **Zeeman effect (p. 155)** to measure magnetic fields on the sun. The average sunspot contains magnetic fields a few thousand times stronger than Earth's. This is part of the evidence that the sunspot cycle is produced by a solar magnetic cycle.
- ▶ The sunspot cycle does not repeat exactly each cycle, and the decades from 1645 to 1715, known as the **Maunder minimum (p. 155)**, seem to have been a time when solar activity was very low and Earth's climate was slightly colder.
- ▶ Sunspots are the visible consequences of **active regions (p. 155)** where the sun's magnetic field is strong. Arches of magnetic field can produce sunspots where the field passes through the photosphere.
- ▶ The sun's magnetic field is produced by the **dynamo effect (p. 158)** operating at the base of the convection zone.
- ▶ Alternate sunspot cycles have reversed magnetic polarity, which has been explained by the **Babcock model (p. 158)**, in which the **differential rotation (p. 158)** of the sun winds up the magnetic field. Tangles in the field arch above the surface and cause active regions visible to your eyes as sunspot pairs. When the field becomes strongly tangled, it reorders itself into a simpler but reversed field, and the cycle starts over.
- ▶ Arches of magnetic field are visible as **prominences (p. 162)** in the chromosphere and corona. Seen from above in filtergrams, prominences are visible as dark **filaments (p. 162)** silhouetted against the bright chromosphere.
- ▶ **Reconnections (p. 163)** of magnetic fields can produce powerful **flares (p. 163)**, sudden eruptions of X-ray, ultraviolet, and visible radiation plus high-energy atomic particles. Flares are important because they can have dramatic effects on Earth, such as communications blackouts.
- ▶ The solar wind originates in regions on the solar surface called **coronal holes (p. 163)**, where the sun's magnetic field leads out into space and does not loop back to the sun.
- ▶ **Coronal mass ejections, or CMEs (p. 163)**, occur when magnetic fields on the surface of the sun eject bursts of ionized gas that flow outward in the solar wind. Such bursts can produce **auroras (p. 163)** and other phenomena if they strike Earth.
- ▶ Other stars are too far away for starspots to be visible, but some stars vary in brightness in ways that show they have spots on their surfaces. Also, spectroscopic observations reveal that many other stars have spots and magnetic fields that follow long-term cycles like the sun's.
- ▶ Small changes in the **solar constant (p. 161)** over decades can affect Earth's climate and may be responsible for the Little Ice Age and other climate fluctuations in Earth's history.

Review Questions

1. Why can't you see deeper into the sun than the photosphere?
2. What evidence can you give that granulation is caused by convection?
3. How are granules and supergranules related? How do they differ?
4. How can astronomers detect structure in the chromosphere?
5. What evidence can you give that the corona has a very high temperature?
6. What heats the chromosphere and corona to a high temperature?
7. How are astronomers able to explore the layers of the sun below the photosphere?
8. Why does nuclear fusion require high temperatures?
9. Why does nuclear fusion in the sun occur only near the center?
10. How can astronomers detect neutrinos from the sun?
11. How did neutrino oscillation affect the detection of solar neutrinos by the Davis experiment?
12. What evidence can you give that sunspots are magnetic?
13. How does the Babcock model explain the sunspot cycle?
14. What does the spectrum of a prominence reveal? What does its shape reveal?
15. How can solar flares affect Earth?
16. **How Do We Know?** What does it mean when scientists say they are certain? What does scientific certainty really mean?
17. **How Do We Know?** How does consolidation extend scientific understanding?

Discussion Questions

1. What energy sources on Earth cannot be thought of as stored sunlight?
2. What would the spectrum of an auroral display look like? Why?

3. What observations would you make if you were ordered to set up a system that could warn astronauts in orbit of dangerous solar flares? Such a warning system exists.

Problems

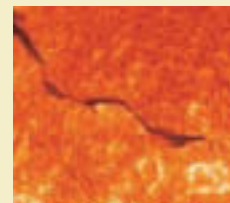
1. The radius of the sun is 0.7 million km. What percentage of the radius is taken up by the chromosphere?
2. The smallest detail visible with ground-based solar telescopes is about 1 arc second. How large a region does this represent on the sun? (*Hint:* Use the small-angle formula, Chapter 3.)
3. What is the angular diameter of a star like the sun located 5 ly from Earth? Is the Hubble Space Telescope able to detect detail on the surface of such a star?
4. How much energy is produced when the sun converts 1 kg of mass into energy?
5. How much energy is produced when the sun converts 1 kg of hydrogen into helium? (*Hint:* How does this problem differ from Problem 4?)
6. A 1-megaton nuclear weapon produces about 4×10^{15} J of energy. How much mass must vanish when a 5-megaton weapon explodes?
7. A solar flare can release 10^{25} J. How many megatons of TNT would be equivalent?
8. The United States consumes about 2.5×10^{19} J of energy in all forms in a year. How many years could you run the United States on the energy released by the solar flare in Problem 7?
9. Use the luminosity of the sun, the total amount of energy it emits each second, to calculate how much mass it converts to energy each second.
10. If a sunspot has a temperature of 4200 K and the solar surface has a temperature of 5800 K, how many times brighter is a square meter of the surface compared to a square meter of the sunspot? (*Hint:* Use the Stefan–Boltzmann law, Chapter 7.)
11. Neglecting energy absorbed or reflected by Earth’s atmosphere, the solar energy hitting 1 square meter of Earth’s surface is 1370 J/s. How long does it take a baseball diamond (90 ft on a side) to receive 1 megaton of solar energy?

Learning to Look

1. Whenever there is a total solar eclipse, you can see something like the image shown at right. Explain why the shape and extent of the glowing gases is different for each eclipse.
2. The two images at right show two solar phenomena. What are they, and how are they related? How do they differ?
3. This image of the sun was recorded in the extreme ultraviolet by the SOHO spacecraft. Explain the features you see.



NOAO



NOAO



NASA/SOHO

9

The Family of Stars



Visual wavelength image

Guidepost

Science is based on measurement, but measurement in astronomy is very difficult. To discover the properties of stars, astronomers must use their telescopes and spectrographs in ingenious ways to learn the secrets hidden in starlight. The result is a family portrait of the stars.

Here you will find answers to five essential questions about stars:

- **How far away are the stars?**
- **How much energy do stars make?**
- **How big are stars?**
- **How much mass do stars contain?**
- **What is the typical star like?**

With this chapter, you leave our sun behind and begin your study of the billions of stars that dot the sky. In a sense, the star is the basic building block of the universe. If you hope to understand what the universe is, what our sun is, what our Earth is, and what we are, you need to understand stars.

Once you know how to find the basic properties of stars, you will be ready to trace the history of the stars from birth to death, a story that begins in the next chapter.

The center of the gas cloud around the star V838 Monocerotis is ablaze with the light of brilliant stars, but fainter stars also dot the image. The crosses on the star images are produced by light diffraction in the telescope. (NASA/Hubble Heritage Project)

*Ice is the silent language of the peak;
and fire the silent language of the star.*

— CONRAD AIKEN, *AND IN THE HUMAN HEART*

DOES YOUR FAMILY include some characters? The family of stars is amazingly diverse. In a photograph such as ■ Figure 9-1, stars seem to differ only slightly in color and brightness, but you are going to discover that some are huge and some are tiny, some are astonishingly hot and some are quite cool, some are ponderously massive and some are tiny little stars hardly massive enough to shine. If your family is as diverse as the family of stars, you may have some peculiar relatives.

Unfortunately, finding out what a star is like is quite difficult. When you look at a star, you look across a vast distance and see only a bright point of light. Just looking tells you almost nothing about a star's energy production, diameter, or mass. Rather than just look at stars, you have to analyze starlight with great care. Starlight is the silent language of the sky, and it speaks volumes.

9-1 Measuring the Distances to Stars

ALTHOUGH YOU WANT TO LEARN such things as the size and mass of stars, you immediately meet a detour. To find out almost anything about a star, you must know how far away it is. That quick detour will provide you with a method of measuring the distances to stars.

Distance is the most difficult measurement in astronomy, and astronomers have found a number of ways to estimate the distance to stars. Yet each of those ways depends on a direct geometrical method that is much like the method surveyors use to measure the distance across a river they cannot cross. You can begin by reviewing that method and then apply it to stars.

The Surveyor's Triangulation Method

To measure the distance across a river, a team of surveyors begins by driving two stakes into the ground a known distance apart. The distance between the stakes is the baseline of the measurement. The surveyors then choose a landmark on the opposite side of the river, a tree perhaps, thus establishing a large triangle marked by the two stakes and the tree. Using their surveying instruments, they sight the tree from the two ends of the baseline and measure the two angles on their side of the river (■ Figure 9-2).

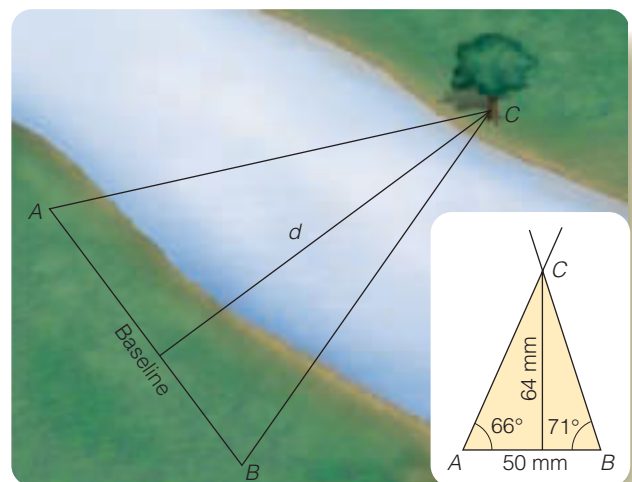
Now that they know two angles of this large triangle and the length of the side between the angles, the surveyors can find the distance across the river by simple trigonometry. Another way to find the distance is to construct a scale drawing. For example, if the baseline is 50 m and the angles are 66° and 71° , you can draw a line 50 mm long to represent the baseline. Each millimeter on



■ **Figure 9-1**

The modern quest to understand the universe is symbolized in this photo of the Eta Carinae Nebula, roughly 7500 light-years from Earth. Only by the careful analysis of starlight have astronomers learned that the stars in the nebula are only 3 million years old and that the brightest star at lower left contains 100 times more matter than the sun. (2MASS Sky Survey and IPAC)

your drawing is worth 1 meter. Using a protractor, you can construct angles of 66° and 71° at each end of the baseline, and then, as shown in Figure 9-2, extend the two sides until they meet at C . Point C on your drawing is the location of the tree. If you measure the height of your triangle, you would find it to be 64 mm and thus conclude that the distance from the baseline to



■ **Figure 9-2**

You can find the distance d across a river by measuring the length of the baseline and the angles A and B , and then constructing a scale drawing of the triangle.

the tree is 64 m. Modern surveyors use calculators to do the math; but, however you solve the problem, the point is that simple triangulation can reveal the distance across a river.

The more distant an object is, the longer the baseline you need to measure its distance. You could use a baseline 50 m long to find the distance across a river; but, to measure the distance to a mountain on the horizon, you might need a baseline 1000 m long. Great distances require long baselines.

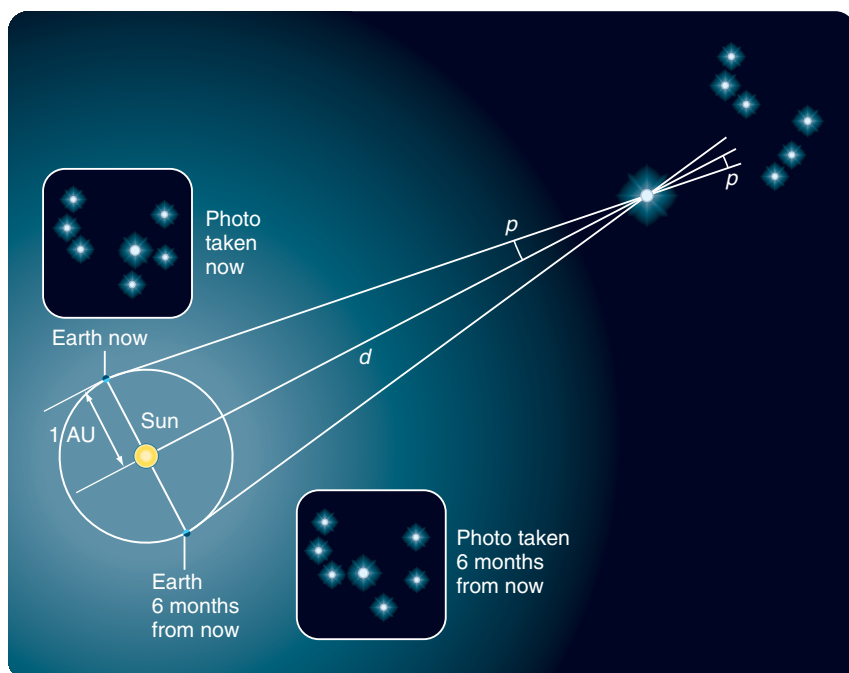
The Astronomer's Triangulation Method

To find the distance to a star, you must use a very long baseline, the diameter of Earth's orbit. If you take a photograph of a nearby star and then wait six months, Earth will have moved halfway around its orbit. You can then take another photograph of the star from the other side of Earth's orbit 2 AU (astronomical units) from the point where the first photograph was taken. Thus your baseline equals the diameter of Earth's orbit, or 2 AU, and lines to the star outline a long thin triangle (■ Figure 9-3).

You then have two photographs of the same part of the sky taken from slightly different locations in space. When you examine the photographs, you will discover that the nearby star is not in exactly the same place in the two photographs. This apparent shift in the position of the star is called *parallax*, the apparent

■ Figure 9-3

You can measure the parallax of a nearby star by photographing it from two points along Earth's orbit. For example, you might photograph it now and again in six months. Half of the star's total change in position from one photograph to the other is its stellar parallax, p .



change in the position of an object due to a change in the location of the observer. In Chapter 4, you saw an everyday example. Your thumb, held at arm's length, appears to shift position against a distant background when you look with first one eye and then with the other (see page 56). In this case, the baseline is the distance between your eyes, and the parallax is the angle through which your thumb appears to move when you change eyes. The farther away you hold your thumb, the smaller the parallax.

Because the stars are so distant, their parallaxes are very small angles, usually expressed in arc seconds. The quantity that astronomers call **stellar parallax (p)** is half the total shift of the star, in other words, the shift as seen over a 1 AU baseline, as shown in Figure 9-3. Astronomers measure the parallax, and surveyors measure the angles at the ends of the baseline, but both measurements reveal the same thing—the shape and size of the triangle and thus the distance to the object in question.

Astronomers have defined a special unit of distance, the **parsec (pc)**,* for use in distance calculations. A parsec is defined as the distance to an imaginary star with a parallax of 1 arc second. One parsec turns out to equal 2.06×10^5 AU, or 3.26 ly. This makes it very easy to calculate the distance to a star given the parallax. The formula is simply:

$$d = \frac{1}{p}$$

where the parallax, p , is expressed in arc seconds and the distance, d , is expressed in parsecs. For example, one of your Favorite Stars, Sirius, has a parallax of 0.379 arc seconds. That means the distance to Sirius in parsecs is 1 divided by 0.379, which equals 2.64 pc. If you want to convert to light-years, multiply 2.64 pc by 3.26 ly/pc, and you find that Sirius is 8.61 ly away.

Measuring the parallax p is very difficult because it is such a small angle. The star nearest the sun is one of your Favorite Stars, α Centauri. It has a parallax of only 0.742 arc seconds, and the more distant stars have even smaller parallaxes. To see how small these angles are, hold a piece of paper edgewise at arm's length. The thickness of the paper covers an angle of about 30 arc seconds.

The blurring caused by Earth's atmosphere smears star images and makes them about 1 arc second in diameter, and that makes it difficult to measure parallax from Earth. Even when astronomers average together many observations, they cannot measure parallax from an observatory on Earth with an uncertainty smaller than about 0.002 arc seconds. If you measure a parallax of

*The parsec is used throughout astronomy because it simplifies the calculation of distance. However, there are instances when the light-year is also convenient. Consequently, the chapters that follow use either parsecs or light-years as convenience and custom dictate.

0.02 arc seconds, the uncertainty is about 10 percent. Ten percent is about the largest uncertainty in a parallax measurement that astronomers can comfortably tolerate, so ground-based astronomers have not been able to measure the distance to stars farther distant than about 50 pc. Ever since the first stellar parallax was measured in 1838, ground-based astronomers have been able to measure accurate parallaxes for only about 10,000 stars.

In 1989, the European Space Agency launched the satellite Hipparcos to measure stellar parallaxes from orbit above the blurring effects of Earth's atmosphere. The satellite observed for four years, and the data were reduced by highly sophisticated software to produce two parallax catalogs in 1997. One catalog contains 120,000 stars with parallaxes 20 times more accurate than ground-based measurements. The other catalog contains over a million stars with parallaxes as accurate as ground-based parallaxes. The Hipparcos data have given astronomers new insights into the nature of stars.

The European Space Agency plans to launch the GAIA mission in a few years. It will be able to measure the parallax of a billion stars to 10 percent. NASA's planned Space Interferometry Mission will be able to measure the distances of stars out to 25,000 pc.

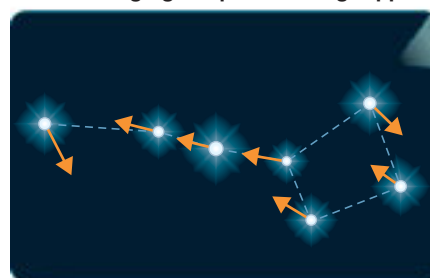
Proper Motion

Parallax isn't the only way to find the distances to the stars. A related technique uses the motions of the stars. All the stars in the sky, including the sun, are moving along orbits around the center of our galaxy. That motion isn't obvious over periods of years, but over the centuries it can significantly distort the shape of constellations (■ Figure 9-4). Detecting the slow drift of the stars requires high-precision measurements, but it can reveal information about the distances to the stars.

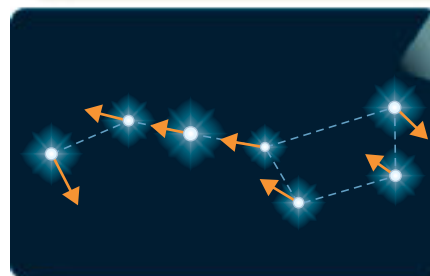
If you photograph a small area of the sky on two dates separated by 10 years or more, precise measurements would reveal that some of the stars in the photograph have moved very slightly against the background of more distant stars. This motion, expressed in units of arc seconds per year, is the **proper motion** of the stars. As examples, consider two stars from your list of Favorite Stars. Vega is a bright blue-white star in the summer sky, and it has a proper motion of 0.351 arc seconds per year. Rigel, a bright blue-white star in the winter sky, has a proper motion of only 0.002 arc seconds per year. The two stars are nearly the same brightness in the sky and nearly the same temperature, but the proper motion of Rigel is over a hundred times less than that of Vega. What does that mean?

A star might have a small proper motion if it is moving almost directly toward or away from you; then its position on the sky would change very slowly. That is unlikely, but it does happen. Another reason a star might have a small proper motion is that it could be quite far away from you. Then even if the star were moving rapidly through space, it would not have a large

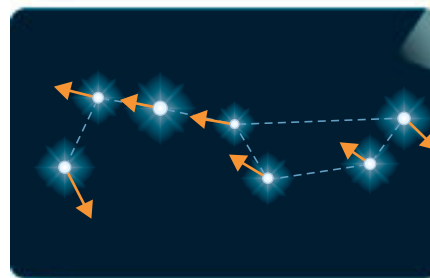
The Changing Shape of the Big Dipper



100,000 years ago the Big Dipper had a different shape.



Proper motion is moving the stars of the Big Dipper across the sky.



100,000 years in the future, the Big Dipper will have a distorted shape.

■ **Figure 9-4**

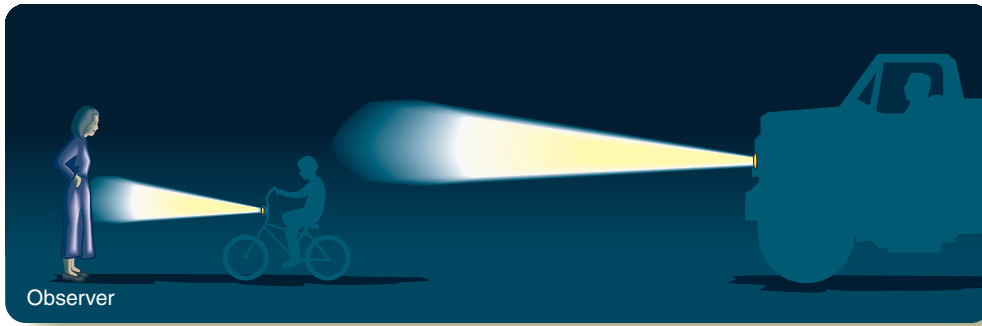
Proper motion refers to the slow movement of the stars across the sky.

proper motion. That explains why Rigel, at a distance of 237 pc, has a smaller proper motion, and Vega, at a distance of only 7.76 pc, has a larger proper motion. Although Rigel is 31 times farther away than Vega, they have nearly the same brightness in the sky. Rigel must be emitting a lot more light than Vega.

Astronomers can use proper motion to look for nearby stars. If you see a star with a small (or zero) proper motion, it is probably a distant star, but a star with a large proper motion is probably quite close. You may have seen this effect if you watch birds. Distant geese move slowly across the sky, but a nearby bird flits quickly across your field of view. Proper motions can help astronomers locate nearby stars for further study.

9-2 Apparent Brightness, Intrinsic Brightness, and Luminosity

IF YOU SEE A LIGHT on a dark highway, it is hard to tell how powerful it really is. It could be the brilliant headlight on a distant truck or the dim headlight on a nearby bicycle (■ Figure 9-5).



■ **Figure 9-5**

To judge the true brightness of a light source, you need to know how far away it is. With no clues to distance, the headlight on a distant truck might look as bright as the nearby headlight on a bicycle.

How bright an object looks depends not only on how much light it emits but also on its distance.

A sixth-magnitude star just visible to your eye looks faint, but its apparent magnitude doesn't tell you how luminous it really is. Now that you know how to find the distance to stars, you can use those distances to figure out the **intrinsic brightness** of the stars. *Intrinsic* means “belonging to the thing,” so the intrinsic brightness of a star refers to the total amount of light the star emits.

Brightness and Distance

When you look at a bright light, your eyes respond to the visual wavelength energy falling on your eye's retina. The apparent brightness you perceive is related to the flux of energy entering your eye. **Flux** is the energy in joules (J) per second falling on 1 square meter. Recall that a joule is about as much energy as is released when an apple falls from a table onto the floor. One joule per second is one watt, a common unit of energy consumption used, for example, to rate light bulbs.

The apparent brightness of a light source is described by the inverse square law. (You first encountered the inverse square relation in Chapter 5, where it was applied to the strength of gravity. See Figure 5-6.) If you double the distance to a light source, its brightness falls by a factor of 2^2 or 4 times. If you triple the distance, the brightness falls by a factor of 3^2 , which equals 9 times. The flux of light on a surface is inversely proportional to the square of the distance from the source.

Now you can understand how the brightness of any light source depends on its distance. If you knew both the apparent magnitude of a star and its distance from Earth, you could use the inverse square law to correct for distance and learn the intrinsic brightness of the star. Astronomers do that using a special kind of magnitude scale described in the next section.

Absolute Visual Magnitude

If all stars were the same distance from Earth, you could compare one with another and decide which was emitting more light and which less. Of course, the stars are scattered at different distances,

and you can't shove them around to line them up for comparison. If, however, you know the distance to a star, you can use the inverse square relation to calculate the brightness the star would have at some standard distance. Astronomers have adopted 10 pc as the standard distance and refer to the apparent visual magnitude a star would have if it were 10 pc away as its **absolute visual magnitude** (M_V). This is an expression of the intrinsic brightness of the star.

The symbol for absolute visual magnitude is M_V . The subscript reminds you it is a visual magnitude based only on the wavelengths of light you can see. Other magnitude systems are based on other parts of the electromagnetic spectrum, such as the infrared and ultraviolet.

How does the sun stack up against other stars? Astronomers can find the sun's absolute visual magnitude because they know the distance to the sun and can measure its apparent visual magnitude. The sun is tremendously bright in the sky, but it is very close. Its absolute visual magnitude is only 4.83. If the sun were only 10 pc from Earth (not a great distance in astronomy), it would look no brighter than the faintest star in the handle of the Little Dipper.

The intrinsically brightest stars known have absolute visual magnitudes of about -8 , which means that such a star 10 pc from Earth would be nearly as bright as the moon. In absolute magnitude, such stars are 13 magnitudes brighter than the sun, so they must be emitting over 100,000 times more light than the sun. Yet the intrinsically faintest stars have absolute visual magnitudes of $+15$ or fainter. They are ten magnitudes fainter than the sun, meaning they are emitting 10,000 times less light than the sun.

The detour to find the distance to stars had led you to absolute visual magnitude and some new insights into what stars are like.

Calculating Absolute Visual Magnitude

How exactly do astronomers find the absolute visual magnitude of a star? This question leads to one of the most important formulas in astronomy, a formula that relates a star's magnitude and its distance.

The **magnitude–distance formula** relates the apparent magnitude m_v , the absolute magnitude M_v , and the distance d in parsecs:

$$m_v - M_v = -5 + 5 \log_{10}(d)$$

If you know any two of the parameters in this formula, you can easily calculate the third. If you want to find the absolute magnitude of a star, then you need to know its distance and apparent magnitude. Suppose a star has a distance of 50 pc and an apparent magnitude of 4.5. A calculator tells you that the log of 50 is 1.70, and $-5 + 5(1.70)$ equals 3.5, so you know that the star's absolute magnitude is 3.5 magnitudes brighter than its apparent magnitude. That means the absolute magnitude is 1.0 because 4.5 minus 3.5 is 1.0. (Remember that smaller numbers mean brighter magnitudes.) If this star were 10 pc away, it would look bright in the sky, a first-magnitude star.

Astronomers also use the magnitude–distance formula to calculate the distance to a star if the apparent and absolute magnitudes are known. For that purpose, it is handy to rewrite the formula in the following form:

$$d = 10^{(m_v - M_v + 5)/5}$$

If you knew that a star had an apparent magnitude of 7 and an absolute magnitude of 2, then $m_v - M_v$ is 5 magnitudes, and the distance would be 10^2 or 100 parsecs.

The magnitude difference $m_v - M_v$ is known as the **distance modulus**, a measure of how far away the star is. The larger the distance modulus, the more distant the star. You could use the magnitude–distance formula to construct a table of distance and distance modulus (■ Table 9-1).

■ **Table 9-1** | **Distance Moduli**

$m_v - M_v$	d (pc)
0	10
1	16
2	25
3	40
4	63
5	100
6	160
7	250
8	400
9	630
10	1000
.	.
.	.
.	.
15	10,000
.	.
.	.
20	100,000

The magnitude–distance formula may seem awkward at first, but a calculator makes it easy to use. The formula is important because it performs a critical function in astronomy: It allows astronomers to convert observations of distance and apparent magnitude into absolute magnitude, a measure of true brightness. Once you know the absolute magnitude, you can go one step further and figure out the total amount of energy a star is radiating into space.

Luminosity

The **luminosity** (L) of a star is the total energy the star radiates in one second. Hot stars emit a great deal of ultraviolet radiation that you can't see, and cool stars emit infrared. Because absolute visual magnitude includes only visible radiation, astronomers must add a small correction to make up for the invisible energy. Then they can calculate the luminosity of the star from its absolute magnitude.

The correction astronomers make adjusts for the radiation emitted at wavelengths humans cannot see. The absolute visual magnitudes of hot stars will underestimate their total luminosities because those stars radiate significant amounts of ultraviolet radiation. Similarly the correction for cool stars is large because they radiate significant amounts of infrared. Astronomers can correct for the missing radiation because the amount of missing energy depends only on the star's temperature. For hot and cool stars, the correction can be large, but for medium-temperature stars like the sun, the correction is small. Adding the proper correction to the absolute visual magnitude changes it into the **absolute bolometric magnitude**—the absolute magnitude the star would have if you could see all wavelengths.

To find the luminosity of a star, you compare the star with the sun. If the absolute bolometric magnitude of the star is one magnitude brighter than the sun, then it must be approximately 2.5 times more luminous. If it is five magnitudes brighter, then it must be 100 times more luminous. Astronomers would write the luminosity of the first star as $2.5 L_{\odot}$ and the luminosity of the second star as $100 L_{\odot}$. To find the luminosity of a star in joules per second, you can just multiply by the luminosity of the sun, 3.83×10^{26} J/s. For example, Favorite Star Aldebaran has a luminosity of about $150 L_{\odot}$, which corresponds to about 6×10^{28} J/s.

Remember Favorite Stars Vega and Rigel? Earlier in this chapter you noted that they look the same in the sky, but Rigel is much further away, so it must be more luminous. Now you can calculate their luminosities and discover that Rigel is almost a thousand times more luminous than Vega.

The most luminous stars emit roughly a million times more energy than the sun, and the least luminous stars emit over a thousand times less. Although stars look similar in the sky, they can emit amazingly different amounts of energy. The most luminous emit at least a billion times more energy per second than the least luminous. Clearly, the family of stars contains some interesting characters.

SCIENTIFIC ARGUMENT

How can two stars look the same in the sky but have dramatically different luminosities?

You can answer this question by building a scientific argument that relates three factors: the appearance of a star, its true luminosity, and its distance. The farther away a star is, the fainter it looks, and that is just the inverse square law. Favorite Stars Vega and Rigel have the same apparent visual magnitude, so your eyes must be receiving the same amount of light from them. Parallax observations from the Hipparcos satellite reveal that Rigel is 31 times farther away than Vega, so Rigel is much more luminous than Vega.

Distance is often the key to understanding the brightness of stars, but temperature can also be important. Build a scientific argument to answer the following: **Why must astronomers make a correction in converting the absolute visual magnitude of very hot or very cool stars into luminosities?**

9-3 The Diameters of Stars

NOW THAT YOU KNOW the luminosities of stars, you are ready to find their diameters. You know little about stars until you know their diameters. Are they all the same size as the sun, or are some larger and some smaller?

Recall that astronomers cannot see the stars as disks through astronomical telescopes (see Chapter 6). All stars look like points of light, no matter how big the telescope. Nevertheless, there is a way to find out how big stars really are. If you know their temperatures and luminosities, you can find their diameters. This relationship will introduce you to the most important diagram in astronomy, where you will discover more of the stars' family secrets.

Luminosity, Radius, and Temperature

To use the luminosity and temperature of a star to learn its diameter, you must first understand the two factors that affect a star's luminosity, surface area and temperature. You can eat dinner by candlelight because a candle flame has a small surface area. Although the flame is very hot, it cannot radiate much heat; it has a low luminosity. However, if the candle flame were 12 ft tall, it would have a very large surface area from which to radiate, and, although it might be no hotter than a normal candle flame, its luminosity would drive you from the table (■ Figure 9-6).

In a similar way, a hot star may not be very luminous if it has a small surface area, but it could be highly luminous if it were larger and had a larger surface area from which to radiate. On the other hand, even a cool star could be luminous if it had a large surface area. Because of this dependence on both temperature and surface area, you need to separate the effects of temperature and surface area, and then you can find the diameters of stars.

Stars are spheres, and the surface area of a sphere is $4\pi R^2$. If you express radius in meters, the area is the

number of square meters on the surface of the star. Each square meter radiates like a blackbody, and you will remember from Chapter 7 that the total energy given off each second from each square meter is σT^4 . So the total luminosity of the star is the surface area multiplied by the energy radiated per square meter:

$$L = 4\pi R^2 \sigma T^4$$

If you divide by the same quantities for the sun, you can cancel out the constants and get a simple formula for the luminosity of a star in terms of its radius and temperature:

$$\frac{L}{L_{\odot}} = \left(\frac{R}{R_{\odot}}\right)^2 \left(\frac{T}{T_{\odot}}\right)^4$$

Here the symbol \odot stands for the sun, and the formula says that the luminosity of a star in terms of the sun equals the radius of the star in terms of the sun squared times the temperature of the star in terms of the sun raised to the fourth power.

Suppose a star is 10 times the sun's radius but only half as hot. How luminous would it be?

$$\frac{L}{L_{\odot}} = \left(\frac{10}{1}\right)^2 \left(\frac{1}{2}\right)^4 = \left(\frac{100}{1}\right) \left(\frac{1}{16}\right) = 6.25$$

The star would be 6.25 times more luminous than the sun.

How can you use this formula to find the diameters of the stars? If you see a cool star that is very luminous, you know it must be very large, and if you see a hot star that is not very luminous, you know it must be very small. Suppose that a star is 40 times the luminosity of the sun and twice as hot. If you put these numbers into the formula, you get:

$$\frac{40}{1} = \left(\frac{R}{R_{\odot}}\right)^2 \left(\frac{2}{1}\right)^4$$

■ Figure 9-6

Molten lava pouring from a volcano is not as hot as a candle flame, but a lava flow has more surface area and radiates more energy than a candle flame. Approaching a lava flow without protective gear is dangerous. (Karafft/Photo Researchers, Inc.)



Solving for the radius, you get:

$$\left(\frac{R}{R_{\odot}}\right)^2 = \frac{40}{2^4} = \frac{40}{16} = 2.5$$

So the radius is:

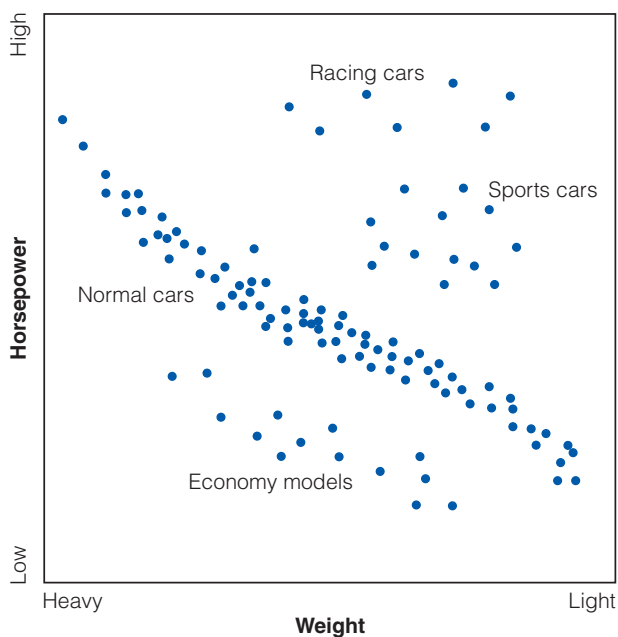
$$\frac{R}{R_{\odot}} = \sqrt{2.5} = 1.58$$

The star is 1.58 times larger in radius than the sun.

The H–R Diagram

The **Hertzsprung–Russell (H–R) diagram**, named after its originators, Ejnar Hertzsprung and Henry Norris Russell, is a graph that separates the effects of temperature and surface area on stellar luminosities and enables astronomers to sort stars according to their diameters. Before you explore the details of the H–R diagram, try looking at a similar diagram you might use to sort automobiles.

You can plot a diagram such as ■ Figure 9-7, showing horsepower versus weight for various makes of cars. In general, the more a car weighs, the more horsepower it has. Most cars fall somewhere along the sequence of cars, running from heavy, high-powered cars at the upper left to light, low-powered models at the lower right. You might call this the main sequence of cars. But some cars have much more horsepower than normal for their weight—the sport and racing models—and lie higher in the diagram. Other cars, the economy models, have less power than normal for cars of the same weight and fall lower in the diagram. Just as this diagram sorts cars into family groups, so the H–R diagram sorts stars into groups according to size.



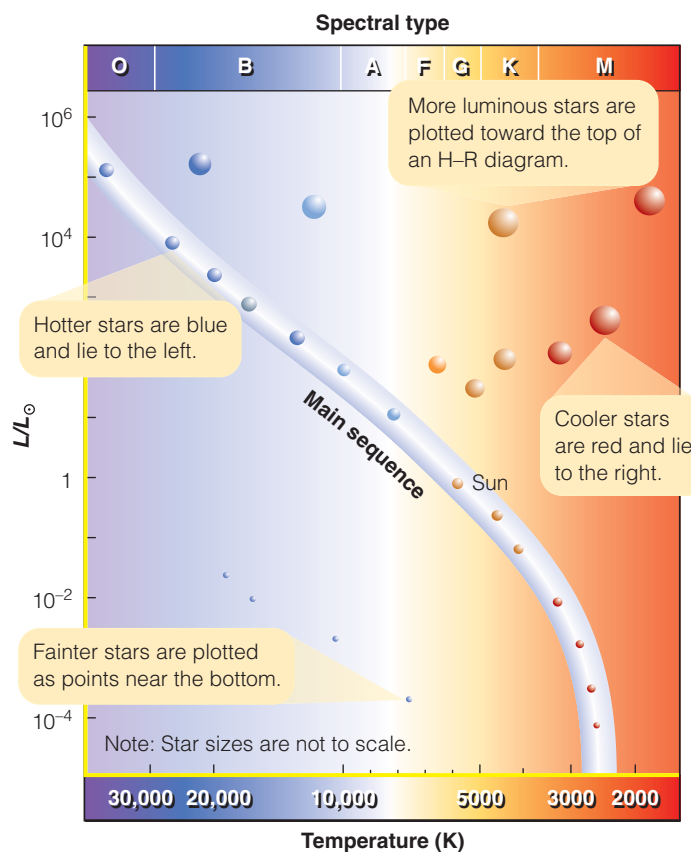
■ **Figure 9-7**

You could analyze automobiles by plotting their horsepower versus their weight and thus reveal relationships between various models. Most would lie somewhere along the main sequence of “normal” cars.

The H–R diagram is a graph with luminosity on the vertical axis and temperature on the horizontal axis. A star is represented by a point on the graph that marks its luminosity and its temperature. The H–R diagram in ■ Figure 9-8 also contains a scale of spectral type across the top. Because a star’s spectral type is determined by its temperature, you could use either spectral type or temperature on the horizontal axis.

In an H–R diagram, the location of a point tells you a great deal about the star it represents. Points near the top of the diagram represent very luminous stars, and points near the bottom represent very-low-luminosity stars. Also, points near the right edge of the diagram represent very cool stars, and points near the left edge of the diagram represent very hot stars. Notice in the H–R diagram in Figure 9-8 how the artist has used color to represent temperature. Red stars are cool, and blue stars are hot.

Astronomers use H–R diagrams so often that they usually skip the words “the point that represents the star.” Rather, they will say that a star is located in a certain place in the diagram. The location of a star in the H–R diagram has nothing to do with the



■ **Figure 9-8**

In an H–R diagram, a star is represented by a dot that shows the luminosity and temperature of the star. The background color in this diagram indicates the temperature of the stars. The sun is a yellow-white G2 star. Most stars fall along a sequence running from hot luminous stars at upper left to cool low-luminosity stars at lower right.

location of the star in space. Furthermore, a star may move in the H–R diagram as it ages and its luminosity and temperature change, but such motion in the diagram has nothing to do with the star’s motion in space.

Notice that the vertical axis of the H–R diagram is an exponential scale. That’s a convenient way to graph data that covers a wide range. On a graph of body weight, for example, you could plot the weight of a cat at the bottom, your own weight just above that, and above that the weight of an elephant and then a whale. You could get all of your data on one graph, but notice that an exponential scale compresses the high numbers and spreads out the low numbers. You can see that effect in the H–R diagram.

Giants, Supergiants, and Dwarfs

The **main sequence** is the region of the H–R diagram running from upper left to lower right. It includes roughly 90 percent of all normal stars. In Figure 9-8, the main sequence is represented by a curved line with dots for stars plotted along it. As you might expect, the hot main-sequence stars are more luminous than the cool main-sequence stars.

Notice in the H–R diagram that some cool stars lie above the main sequence. Although they are cool, they are luminous, and that must mean they are larger and have more surface area than main sequence stars of the same temperature. These are called **giant** stars, and they are roughly 10 to 100 times larger than the sun. There are even **supergiant** stars at the top of the H–R diagram that are over a thousand times the sun’s diameter.

At the bottom of the H–R diagram lie the economy models, stars that are very low in luminosity because they are very small. At the bottom end of the main sequence, the **red dwarfs** are not only small, but they are also cool, and that gives them low luminosities. In contrast, the **white dwarfs** lie in the lower left of the H–R diagram and are lower in luminosity than you would expect, given their high temperatures. That must mean they are very small. Although some white dwarfs are among the hottest stars known, they are so small they have very little surface area from which to radiate, and that limits them to low luminosities.

The equation in the previous section can be used to draw precise lines of constant radius across the H–R diagram, and these lines slope down and to the right across the diagram because cooler stars are fainter than hotter stars of the same size. ■ Figure 9-9 plots the luminosities and temperatures of a number of well-known stars along with lines of constant radius. For example, locate the line labeled $1 R_{\odot}$ (1 solar radius) and notice that it passes through the point representing the sun. Any star whose point is located along this line has a radius equal to the sun’s. Next, look at the rest of the stars along the main sequence. They range from a tenth the size of the sun to about ten times as large. Even though the main sequence slopes dramatically down to the right across the diagram, most main-sequence stars are similar in

size. In contrast, the white dwarfs at the lower left of the diagram are extremely small—only about the size of Earth—and the giants and supergiants at the upper right are extremely large compared to the stars of the main sequence.

Notice the great range of sizes among stars. The largest stars are 100,000 times larger than the tiny white dwarfs. If the sun were a tennis ball, the white dwarfs would be grains of sand, and the largest supergiants would be as big as football fields (■ Figure 9-10).

Now you can understand why Favorite Star Rigel is so much more luminous than Vega. They have nearly the same temperature, but Rigel is a supergiant and has a much larger surface area from which to radiate. Another of your Favorite Stars is Betelgeuse in Orion, also a supergiant. If Betelgeuse replaced the sun at the center of our solar system, it would swallow up Mercury, Venus, Earth, and Mars. The largest stars known have radii of about 7 AU; if one of them replaced the sun, it would extend nearly to the orbit of Saturn.

Interferometric Observations of Diameter

Is there any way to check the diameters predicted by the H–R diagram? One way is to use interferometers (see Chapter 6), for example the Center for High Angular Resolution Astronomy (CHARA) Array on Mount Wilson. There, six 1-meter telescopes combine their light to produce the resolving power of a virtual telescope 330 meters in diameter. Such interferometers can resolve the diameters of large, bright, nearby stars.

You can see Favorite Star Vega high in the sky on summer evenings. It is an A0 V star, and observations with the CHARA array confirm that it is about 2.5 times larger in diameter than the sun—about what you would expect from its location in the H–R diagram. The observations also reveal that it is spinning about twice a day compared to once a month for the sun and is flattened, with its poles 2300 K hotter than its equator (■ Figure 9-11).

Observations with interferometers confirm that upper-main-sequence stars are larger than the sun. Altair (A7) is about 50 percent larger than the sun, and Regulus, a B7 star bright in the sky on spring evenings, is about four times larger than the sun. Achernar, a B3 star, is still larger. All three of these stars are flattened by their rapid spin, as you can see in Figure 9-11.

Interferometric observations of giant and supergiant stars such as Betelgeuse (M2) show that they are also as large as predicted. Betelgeuse is at least 500 times the sun’s diameter and can sometimes puff itself up to 800 times. In contrast, observations of red dwarfs confirm that although they are quite small, they are 15 to 20 percent bigger than expected. Evidently models of red dwarfs need further refining.

In short, interferometric observations confirm the sizes predicted by the temperatures and luminosities on the H–R

■ **Figure 9-9**

An H-R diagram showing the luminosity and temperature of many well-known stars. The dashed lines are lines of constant radius. The star sizes on this diagram are not to scale. (Individual stars that orbit each other are designated A and B, as in Spica A and Spica B.)

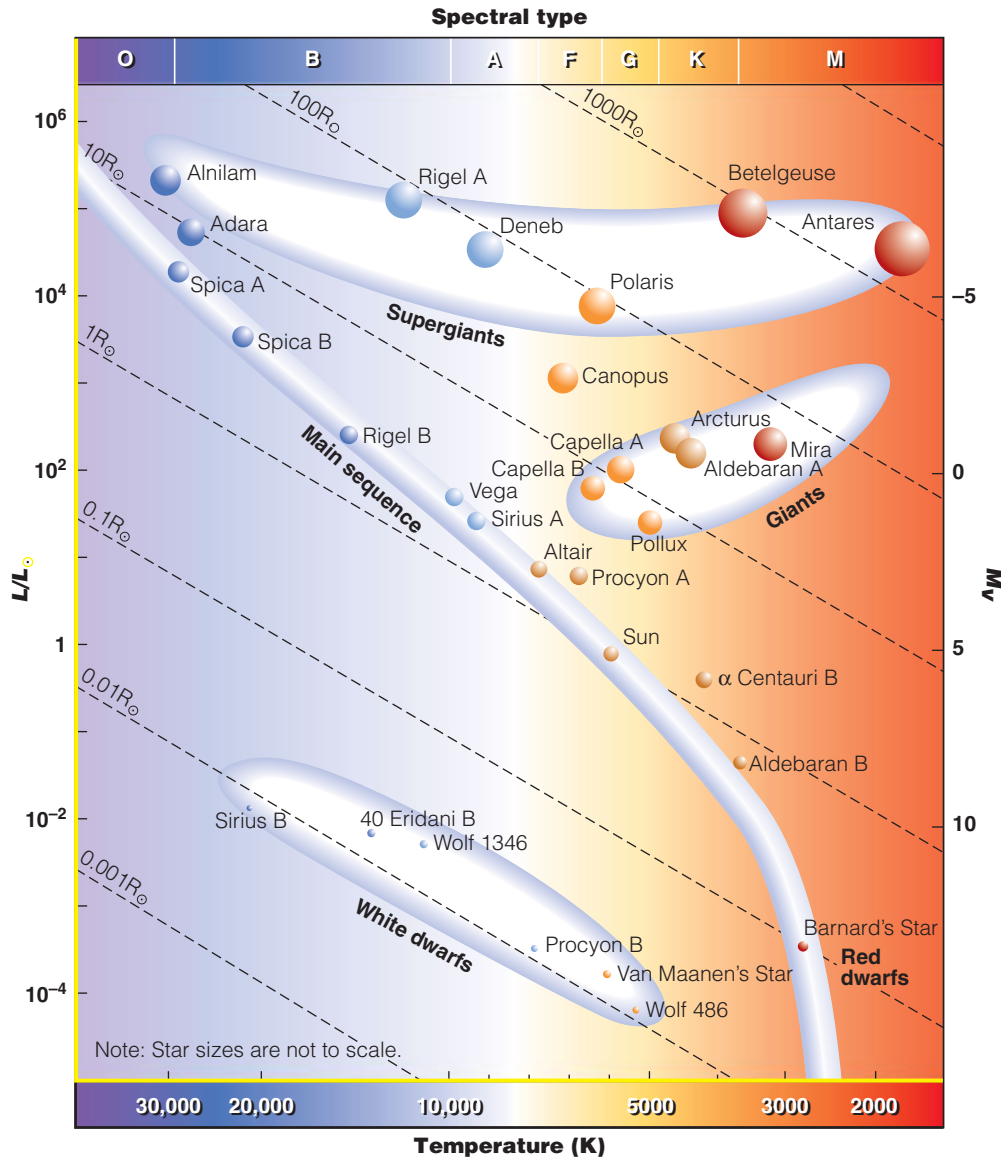


diagram. Stars really do range from roughly the size of Earth to over a thousand times bigger than the sun.

Luminosity Classification

A star's spectrum contains clues as to whether it is a main-sequence star, a giant, or a supergiant. The larger a star is, the less dense its atmosphere is, and that affects the widths of spectral lines.

Atoms collide often in a dense gas, their energy levels become distorted, and their spectral lines broadened. Hydrogen Balmer lines are an example. In the spectrum of a main-sequence star, the Balmer lines are broad because the star's atmosphere is dense and the hydrogen atoms collide often. In the spectrum of a giant star, the lines are narrower (■ Figure 9-12) because the giant star's atmosphere is less dense, and the hydrogen atoms collide less often. In the spectrum of a supergiant star, the Balmer lines are very narrow.

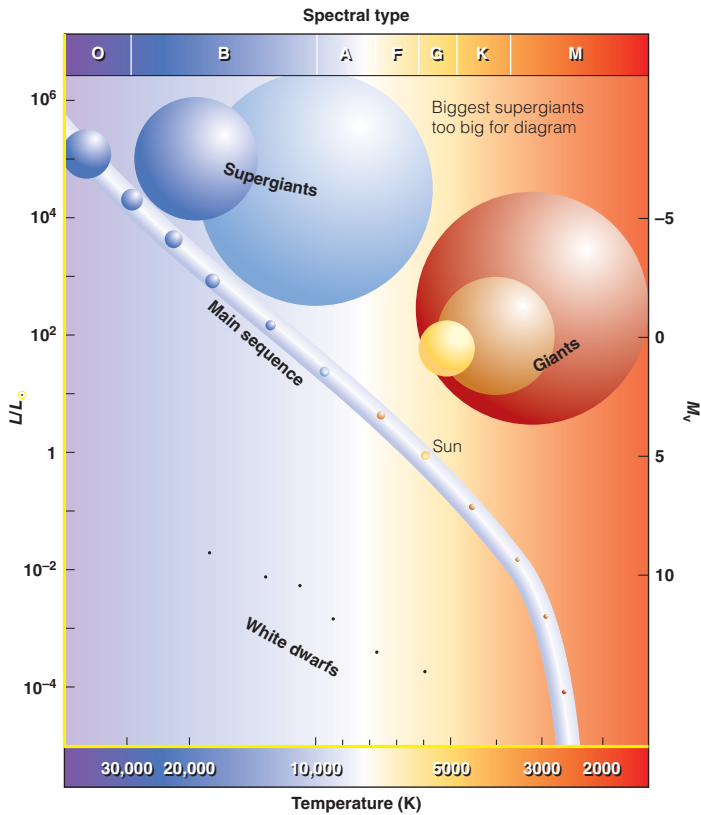
You can look at a star's spectrum and tell roughly how big it is. Size categories derived from spectra are

called **luminosity classes** because the size of the star is the dominating factor in determining luminosity. Supergiants, for example, are very luminous because they are very large. The luminosity classes are represented by the roman numerals I through V, with supergiants further subdivided into types Ia and Ib, as follows:

Luminosity Classes

- Ia Bright supergiant
- Ib Supergiant
- II Bright giant
- III Giant
- IV Subgiant
- V Main-sequence star

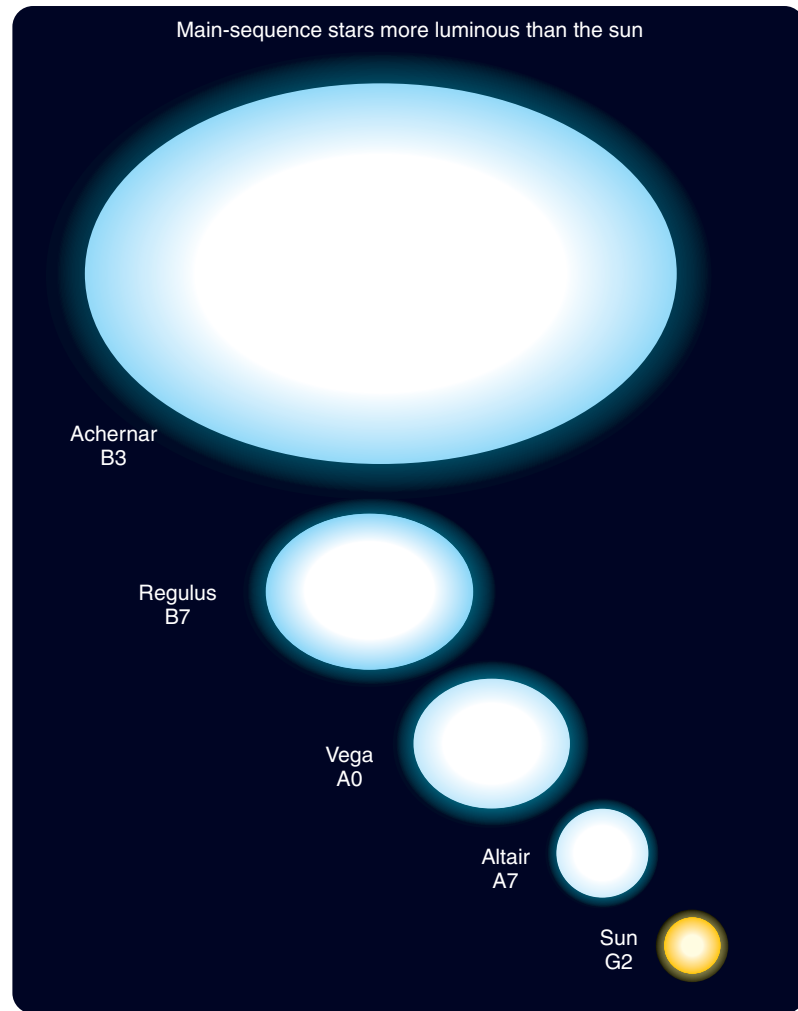
This classification scheme allows you to distinguish between the bright supergiants (Ia) such as Rigel and the regular supergiants (Ib) such as Polaris, the North Star. The star Adhara is a bright



■ **Figure 9-10**

This H-R diagram shows the relative sizes of stars. Giant stars are 10 to 100 times larger than the sun, and white dwarfs are about the size of Earth. (The dots representing white dwarfs here are much too large.) The larger supergiants are too big for this diagram. To visualize the size of the largest stars, imagine that the sun is the size of one of your eyeballs. Then the largest supergiants would be the size of a hot air balloon.

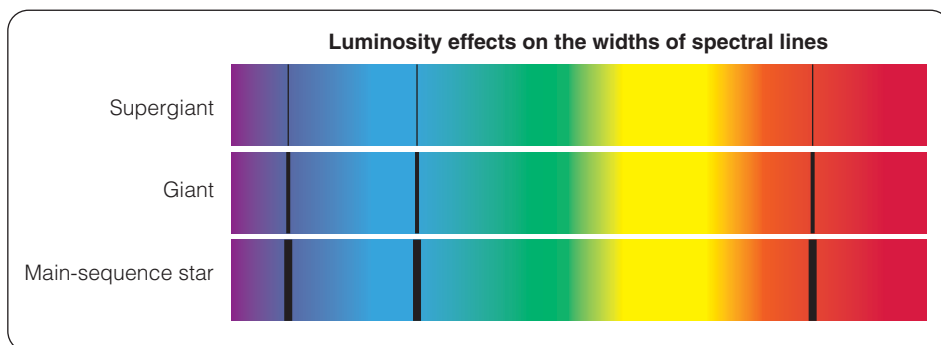
giant (II), Aldebaran is a giant (III), and Altair is a subgiant (IV). Sirius and Vega, like the sun, are main-sequence stars (V). When you describe a star, its luminosity class appears after the spectral type, as in G2 V for the sun. White dwarfs don't enter into this classification because their spectra are peculiar. Notice that some of our Favorite Stars are unusual; next time you look at Polaris, remind yourself that it is a supergiant.



■ **Figure 9-11**

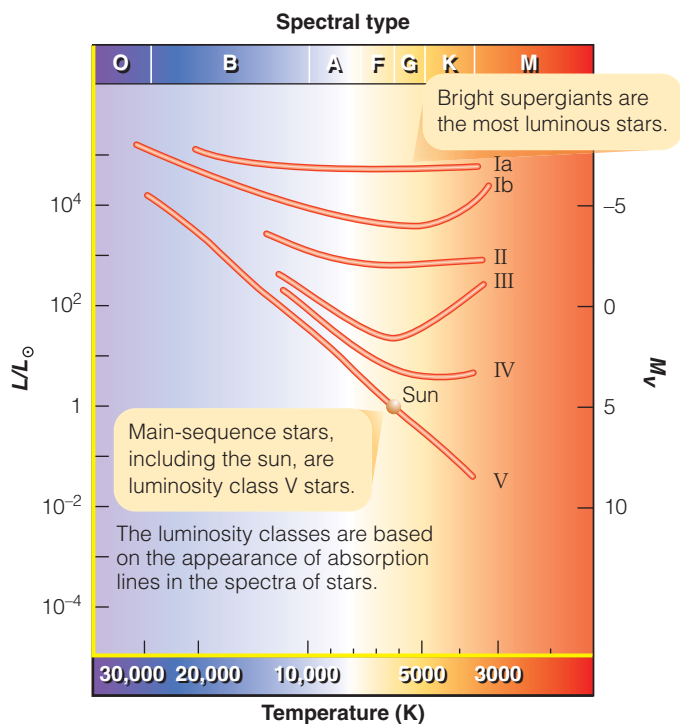
Observations with interferometers can resolve the size and shape of some nearby stars. The stars of the upper main sequence are indeed larger than the sun, as predicted by the H-R diagram. The examples shown here are flattened by rapid rotation, but most stars rotate slower and are more nearly spherical. On the scale of this diagram, the supergiant Beteleguse would have a diameter similar to that of a typical classroom.

The positions of the luminosity classes on the H-R diagram are shown in ■ Figure 9-13. Remember that these are rather broad classifications and that the lines on the diagram are only approximate.



■ **Figure 9-12**

These schematic spectra show how the widths of spectral lines reveal a star's luminosity classification. Supergiants have very narrow spectral lines, and main-sequence stars have broad lines. In addition, certain spectral lines are more sensitive to this effect than others, so careful inspection of a star's spectrum can determine its luminosity classification.



■ **Figure 9-13**

The approximate location of the luminosity classes on the H-R diagram.

A star of luminosity class III may lie slightly above or below the line labeled III. A scale of absolute magnitude has been added to the right edge of this H-R diagram for easy reference.

Luminosity classification is subtle and not too accurate, but it is important in modern astronomy. As you will see in the next section, luminosity classification provides a way to estimate the distance to stars that are too far away to have measurable parallaxes.

Spectroscopic Parallax

Astronomers can measure the stellar parallax of nearby stars, but most stars are too distant to have measurable parallaxes. These distances can be estimated from the star's spectral type, luminosity class, and apparent magnitude in a process called **spectroscopic parallax**. Spectroscopic parallax is potentially a confusing term because it does not involve an actual measurement of parallax shifts, but it is a method to tell you the distance to the star.

Spectroscopic parallax relies on the location of the star in the H-R diagram. If you record the spectrum of a star, you can determine its spectral class, and that tells you its horizontal location in the H-R diagram. You can also determine its luminosity class by looking at the widths of its spectral lines, and that tells you the star's vertical location in the diagram. Once you plot the point that represents the star in the H-R diagram, you can read off its absolute magnitude. As you learned earlier in this chapter, you

can find the distance to a star by comparing its apparent and absolute magnitudes.

For example, Favorite Star Betelgeuse is classified M2 Ib, and its apparent magnitude is about 0.4. You can plot this star in an H-R diagram such as Figure 9-13, where you would find that it should have an absolute magnitude of about -6.0 . That means the distance modulus is 0.4 minus (-6.0) , which is 6.4 , and its distance estimated from Table 9-1 or calculated from the magnitude-distance formula is about 190 pc. Measurements made by the Hipparcos satellite are more accurate and reveal the distance to be 131 pc, with an uncertainty of 21 percent, so the result derived from spectroscopic parallax is only approximate. Obviously a direct measurement of the parallax is better, but for more distant stars spectroscopic parallax is often the only way to find their distance.

SCIENTIFIC ARGUMENT

What evidence can you give that giant stars really are bigger than the sun?

Scientific arguments are based on evidence, so you need to proceed step by step here. Stars exist that have the same spectral type as the sun but are clearly more luminous. Capella, for example, is a G star with an absolute magnitude of 0. Because it is a G star, it must have about the same temperature as the sun, but its absolute magnitude, based on its measured distance, is almost five magnitudes brighter than the sun's. A magnitude difference of five magnitudes corresponds to an intensity ratio of 100, so Capella must be about 100 times more luminous than the sun. If it has the same surface temperature as the sun but is 100 times more luminous, then it must have a surface area 100 times greater than the sun's. Because the surface area of a sphere is proportional to the square of the radius, Capella must be ten times larger in radius. That is clear observational evidence that Capella is a giant star.

In Figure 9-9, you can see that Procyon B is a white dwarf slightly warmer than the sun but about 10,000 times less luminous. Build a scientific argument based on evidence to resolve this question. **Why do astronomers conclude that white dwarfs must be small stars?**

9-4 The Masses of Stars

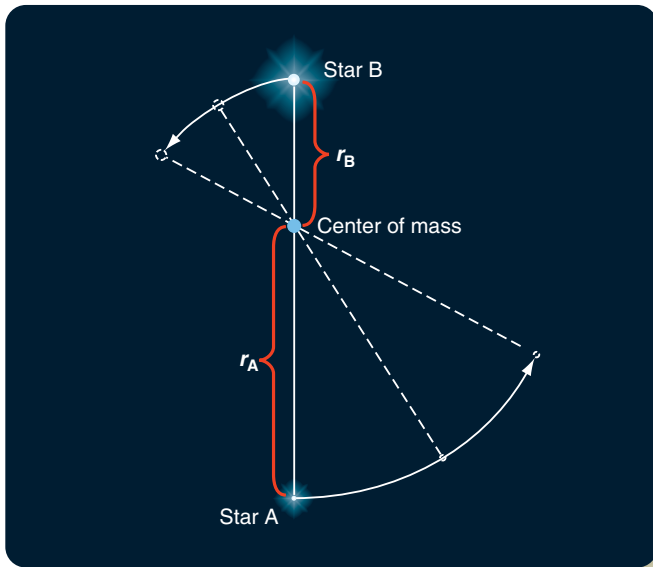
TO UNDERSTAND STARS WELL, you must find out how much matter stars contain, that is, their masses. Do they all contain about the same mass as the sun, or are some more massive and others less? Unfortunately, it's difficult to determine the mass of a star. Looking through a telescope, you see only a point of light that reveals nothing about the mass of the star. Gravity is the key. Matter produces a gravitational field, and you can figure out how much matter a star contains if you watch another object move through the star's gravitational field. To find the masses of stars, you must study **binary stars**, pairs of stars that orbit each other.

Binary Stars in General

To measure the mass of a binary star, you need to understand orbital motion. Chapter 5 illustrated orbital motion by asking you to imagine a cannonball fired from a high mountain (see page 84). If Earth's gravity didn't act on the cannonball, it would follow a straight-line path and leave Earth forever. Because Earth's gravity pulls the cannonball away from its straight-line path, the cannonball follows a curved path around Earth—an orbit. When two stars orbit each other, their mutual gravitation pulls them away from straight-line paths and makes them both follow closed orbits around a point between the stars.

Each star in a binary system moves in its own orbit around the system's center of mass, the balance point of the system. If the stars were connected by a massless rod and placed in a uniform gravitational field such as that near Earth's surface, the system would balance at its center of mass like a playground seesaw (see page 85). If one star is more massive than its companion, then the more massive star is closer to the center of mass and travels in a smaller orbit, while the lower-mass star whips around in a larger orbit (■ Figure 9-14). The ratio of the masses of the stars M_A/M_B equals r_B/r_A , the inverse of the ratio of the radii of the orbits. If one star has an orbit twice as large as the other star's orbit, then it must be half as massive. Getting the ratio of the masses is easy, but that doesn't tell you the individual masses of the stars, which is what you really want to know. That takes further analysis.

To find the mass of a binary star system, you must know the sizes of the orbits and the orbital period—the length of time the stars take to complete one orbit. The smaller the orbits are and the shorter the orbital period is, the stronger the stars' gravity



■ **Figure 9-14**

As stars in a binary star system revolve around each other, the line connecting them always passes through the center of mass, and the more massive star is always closer to the center of mass.

must be to hold each other in orbit. For example, if two stars whirl rapidly around each other in small orbits, then their gravity must be very strong to prevent their flying away from each other. Such stars would have to be very massive. From the size of the orbits and the orbital period, astronomers can figure out the masses of the stars using Newton's laws.

Calculating the Masses of Binary Stars

According to Newton's laws of motion and gravity, the total mass of two stars orbiting each other is related to the average distance a between them and their orbital period P . If the masses are M_A and M_B , then

$$M_A + M_B = \frac{a^3}{P^2}$$

In this formula, a is expressed in AU, P in years, and the mass in solar masses.

Notice that this formula is related to Kepler's third law of planetary motion (see Table 4-1). Almost all of the mass of the solar system is in the sun. For planets in our solar system, the total mass is 1 solar mass, and the formula becomes $P^2 = a^3$, which is Kepler's third law.

In a binary star system, this formula gives you a way to find the masses of the two stars. If you can find the average distance in AU between the two stars, a , and their orbital period in years, P , the sum of the masses of the two stars is just a^3/P^2 .

Example 1: If you observe a binary system with a period of 32 years and an average separation of 16 AU, what is the total mass? *Solution:* The total mass equals $16^3/32^2$, which equals 4 solar masses.

Example 2: Call the two stars in the previous example A and B. Suppose star A is 12 AU away from the center of mass, and star B is 4 AU away. What are the individual masses? *Solution:* The ratio of the masses must be 12:4, which is the same as 3:1. What two numbers add up to 4 and have the ratio of 3:1? In this case, the answer is easy. Star B must be 3 solar masses, and Star A must be 1 solar mass.

Actually, figuring out the mass of a binary star system is not as easy as it might seem from this discussion. The orbits of the two stars may be elliptical; and, although the orbits lie in the same plane, that plane can be tipped at an unknown angle to your line of sight, further distorting the observed shapes of the orbits. Astronomers must find ways to correct for these distortions. In addition, astronomers analyzing binary systems must first find the distances to them so they can estimate the true size of the orbits in astronomical units. Finding the masses of binary stars requires a number of steps to get from what you can observe to what you really want to know, the masses. Constructing such sequences of steps is an important part of science (**How Do We Know? 9-1**).

Although there are many different kinds of binary stars, three types are especially useful for determining stellar masses. These are discussed separately in the next sections.

Chains of Inference

How do scientists measure something they can't detect? Sometimes scientists cannot directly observe the things they really want to study, so they must construct chains of inference that connect observable parameters to the unobservable quantities they want to know. You can't measure the mass of a star directly, so you must find a way to use what you can observe, orbital period and angular separation, to figure out step by step the parameters you need to calculate the mass.

Consider another example. Geologists can't measure the temperature and density of Earth's interior directly. There is no way to drill a hole to Earth's center and lower a thermometer or recover a sample. However, the speed of vibrations from a distant earthquake depends on the temperature and density of the rock they pass through. Geologists can't measure the speed of the vibrations deep inside Earth;

but they can measure the delays in the arrival times at different locations on the surface, and that allows them to work their way back to the speed and, finally, the temperature and density.

Chains of inference can be non-mathematical. Biologists studying the migration of whales can't follow individual whales for years at a time, but they can observe them feeding and mating in different locations; take into consideration food sources, ocean currents, and water temperatures; and construct a chain of inference that leads back to the seasonal migration pattern for the whales.

This chapter contains a number of chains of inference. Almost all sciences use chains of inference. When you can link the observable parameters step by step to the final conclusions, you gain a strong insight into the nature of science.



San Andreas fault: A chain of inference connects earthquakes to conditions inside Earth. (USGS)

Visual Binary Systems

In a **visual binary system**, the two stars are separately visible in the telescope. Only a pair of stars with large orbits can be separated visually; if the orbits are small, the telescope cannot resolve the star images, and you see only a single point of light. In a visual binary system, you can see each star moving around its orbit.

Astronomers study visual binary systems by measuring the position of the two stars directly at the telescope or in photographs. In either case, the astronomers need measurements over many years to map the orbits. The first frame of ■ Figure 9-15 shows a photograph of Favorite Star Sirius, which is a visual binary system made up of the bright star Sirius A and its white dwarf companion Sirius B. The photo was taken in 1960. Successive frames in Figure 9-15 show the motion of the two stars as observed since 1960 and the orbits the stars follow. The orbital period is 50 years, and astronomers have found accurate masses for both stars.

Visual binary systems are common; more than half of all stars are members of binary star systems, and many of those are visual binaries. Favorite Star Polaris has two stellar companions. Few visual binaries, however, can be analyzed completely. Many are so far apart that their periods are much too long for practical mapping of their orbits. Others are so close together that they are hardly visible as separate stars, and it is difficult to map the shape of their orbits. One of the stars that orbits Polaris, for instance,

orbits with a period over a thousand years, and the other is so close to Polaris that it is hardly visible even with the Hubble Space Telescope.

Spectroscopic Binary Systems

If the stars in a binary system are close together, the telescope, limited by diffraction and seeing, reveals only a single point of light. Only by looking at a spectrum, which is formed by light from both stars and contains spectral lines from both, can astronomers tell that there are two stars present and not one. Such a pair of stars is a **spectroscopic binary**.

■ Figure 9-16 shows a sequence of spectra recorded over a few days as the stars in a spectroscopic binary moved around their orbits. You can see how the spectral line in the top spectrum splits into two components that move apart, move together, merge as they cross, and then move apart again. This is the sure sign of a spectroscopic binary.

To understand the spectra in Figure 9-16, look at the diagrams in ■ Figure 9-17, which show two stars orbiting each other. In the first frame, star A is approaching while star B recedes. In the spectrum, you see a spectral line from star A Doppler shifted toward the blue end of the spectrum while the same spectral line from star B is Doppler shifted toward the red end of the spectrum. As the two stars revolve around their orbits, they alternately approach and recede, and you see small Doppler shifts moving their spectral lines apart and then back together. In a real spectroscopic binary, you

A Visual Binary Star System

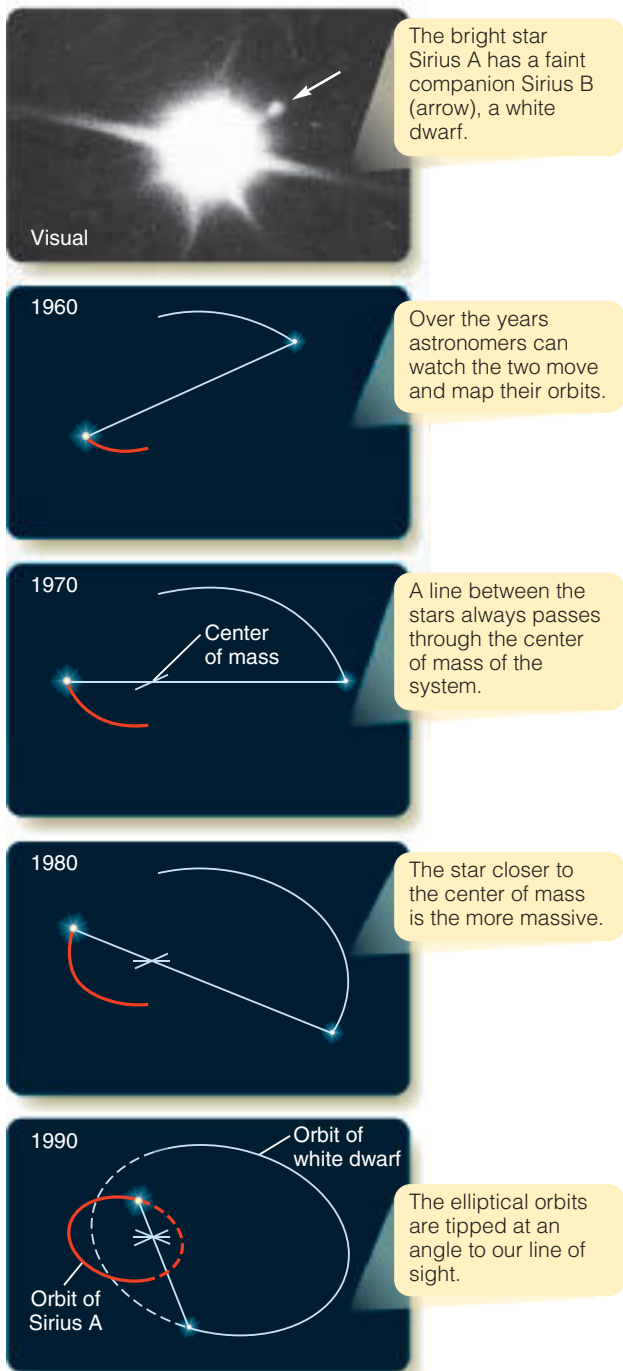


Figure 9-15

The orbital motion of Sirius A and Sirius B can reveal their individual masses. (Photo: © UC Regents Lick Observatory)

can't see the individual stars, but the sight of pairs of spectral lines moving back and forth across each other would alert you that you were observing a spectroscopic binary system.

At first glance, it seems that it should be easy to find the masses of the stars in a spectroscopic binary. You can find the orbital period by waiting to see how long it takes for the spectral lines to return to their starting positions. You can measure the

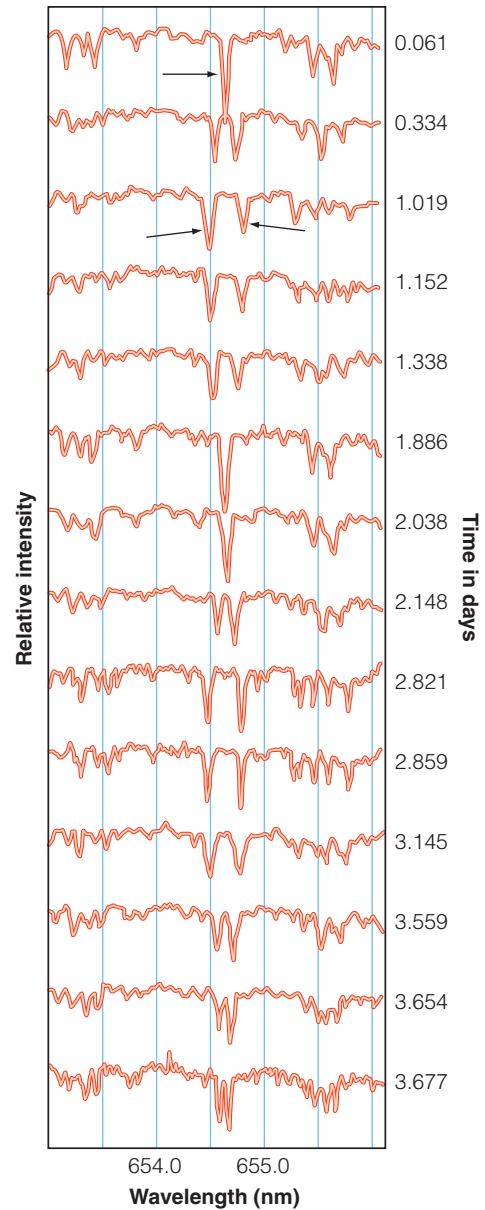
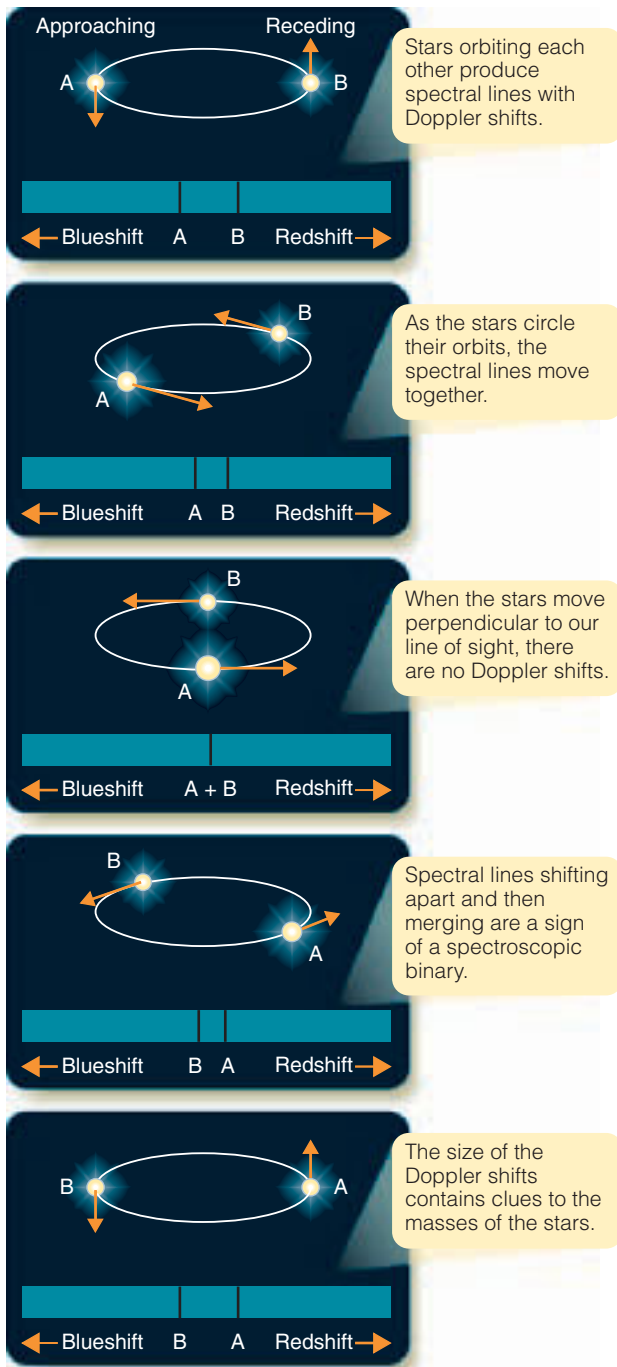


Figure 9-16

Fourteen spectra of the star HD 80715 are shown here as graphs of intensity versus wavelength. A single spectral line (arrow in top spectrum) splits into a pair of spectral lines (arrows in third spectrum), which then merge and split apart again. These changing Doppler shifts reveal that HD 80715 is a spectroscopic binary. (Adapted from data courtesy of Samuel Barden and Harold Nations)

size of the Doppler shifts to find the orbital velocities of the two stars. If you multiply velocity times orbital period, you can find the circumference of the orbit, and from that you can find the radius of the orbit. Now that you know the orbital period and the size of the orbit you should be able to calculate the mass. One important detail is missing, however. You don't know how much the orbits are inclined to your line of sight.

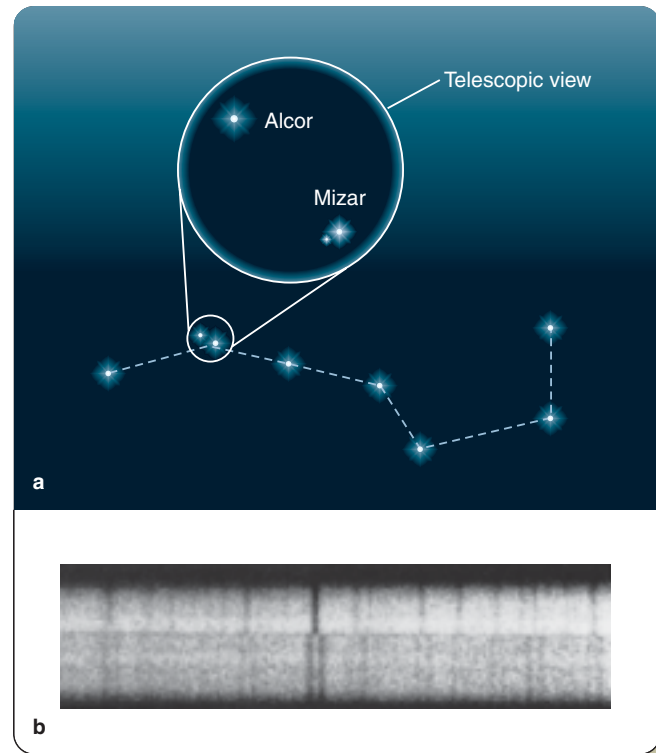
A Spectroscopic Binary Star System



■ **Figure 9-17**

From Earth, a spectroscopic binary looks like a single point of light, but the Doppler shifts in its spectrum reveal the orbital motion of the two stars.

Astronomers can find the inclination of a visual binary system because they can see the shape of the orbits. In a spectroscopic binary system, however, the individual stars are not visible, so the orbits can't be mapped and the inclination can't be found. Recall that the Doppler effect only reveals the radial velocity, the part of the velocity directed toward or away from the observer. Because you cannot find the inclination, you cannot correct these radial



■ **Figure 9-18**

(a) At the bend of the handle of the Big Dipper lie a pair of stars, Mizar and Alcor. Through a telescope you can discover that Mizar has a fainter companion and so is a member of a visual binary system. (b) Spectra of Mizar recorded at different times show that it is itself a spectroscopic binary system rather than a single star. In fact, both the faint companion to Mizar and the nearby star Alcor are also spectroscopic binary systems. (The Observatories of the Carnegie Institution of Washington)

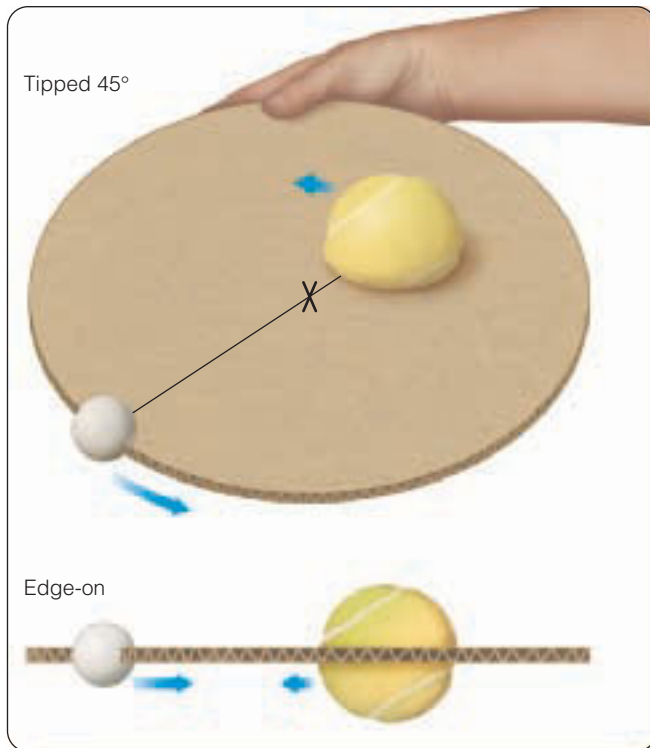
velocities to find the true orbital velocities. Consequently, you cannot find the true masses. All you can find from a spectroscopic binary system is a lower limit to the masses.

More than half of all stars are in binary systems, and most of those are spectroscopic binary systems. Many of the familiar stars in the sky are actually pairs of stars orbiting each other (■ Figure 9-18).

You might wonder what happens when the orbits of a spectroscopic binary system lie exactly edge-on to Earth. The result is the most useful kind of binary system.

Eclipsing Binary Systems

As mentioned earlier, the orbits of the two stars in a binary system always lie in a single plane. If that plane is nearly edge-on to Earth, then the stars will appear to cross in front of each other. Imagine a model of a binary star system in which a cardboard disk represents the orbital plane and balls represent the stars, as in ■ Figure 9-19. If you see the model from the edge, then the balls that represent the stars can move in front of each other as they follow their orbits. The small star crosses in front of the large star, and then, half an orbit later, the large star crosses in front of



■ **Figure 9-19**

Imagine a model of a binary system with tennis and golf balls for stars and a disk of cardboard for the plane of the orbits. Only if you view the system edge on do you see the stars cross in front of each other.

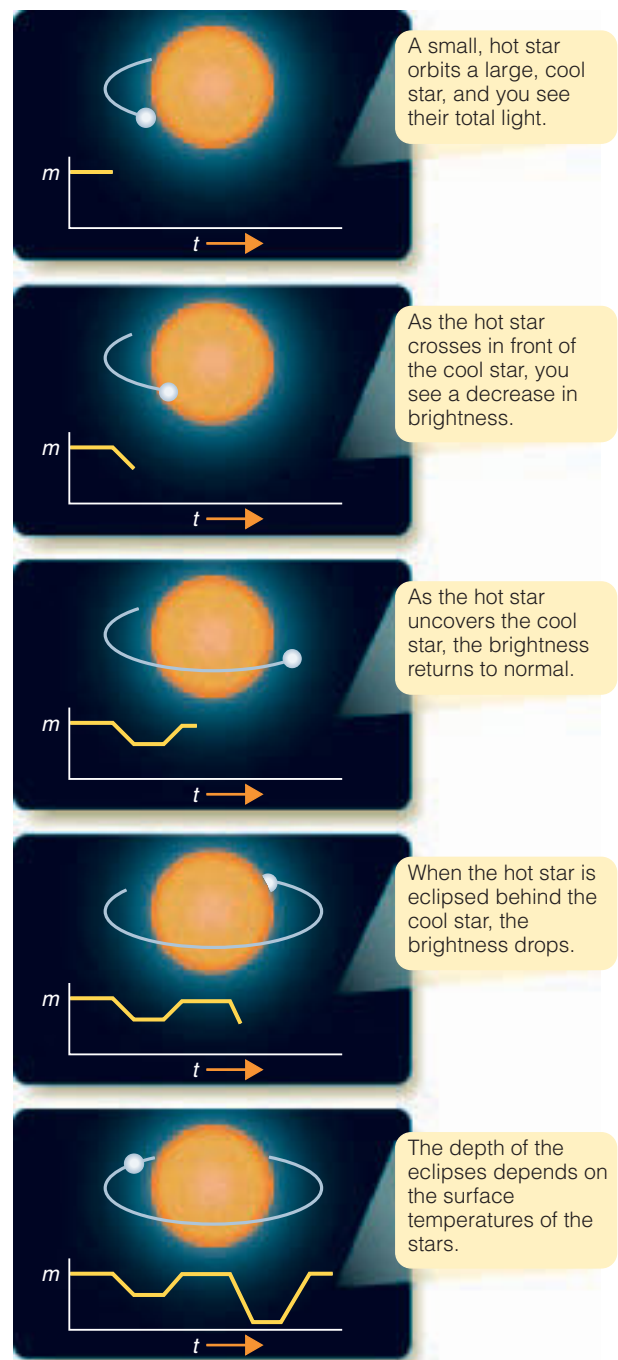
the small star. When one star moves in front of the other, it blocks some of the light, and the star is eclipsed. Such a pair of stars is called an **eclipsing binary**.

Seen from Earth, the two stars are not visible separately. The system looks like a single point of light. But when one star moves in front of the other star, part of the light is blocked, and the total brightness of the point of light decreases. ■ Figure 9-20 shows a smaller star moving in an orbit around a larger star, first eclipsing the larger star and then being eclipsed itself as it moves behind its companion. The resulting variation in the brightness of the system is shown as a graph of brightness versus time, a **light curve**. Remember, you can't see the individual stars in an eclipsing system. Cover the stars in Figure 9-20 with your fingers and look only at the light curve. If you saw such a light curve, you would immediately recognize the point of light in the sky as an eclipsing binary.

The light curves of eclipsing binary systems contain tremendous amounts of information, but the curves can be difficult to analyze. Figure 9-20 shows an idealized system. Compare this with ■ Figure 9-21, which shows the light curve of a real system in which the stars have dark spots on their surfaces and are so close to each other that their shapes are distorted.

Once the light curve of an eclipsing binary system has been accurately observed, you can construct a chain of inference leading to the masses of the two stars. You can find the orbital period easily, and you can get spectra showing the Doppler shifts of the

An Eclipsing Binary Star System

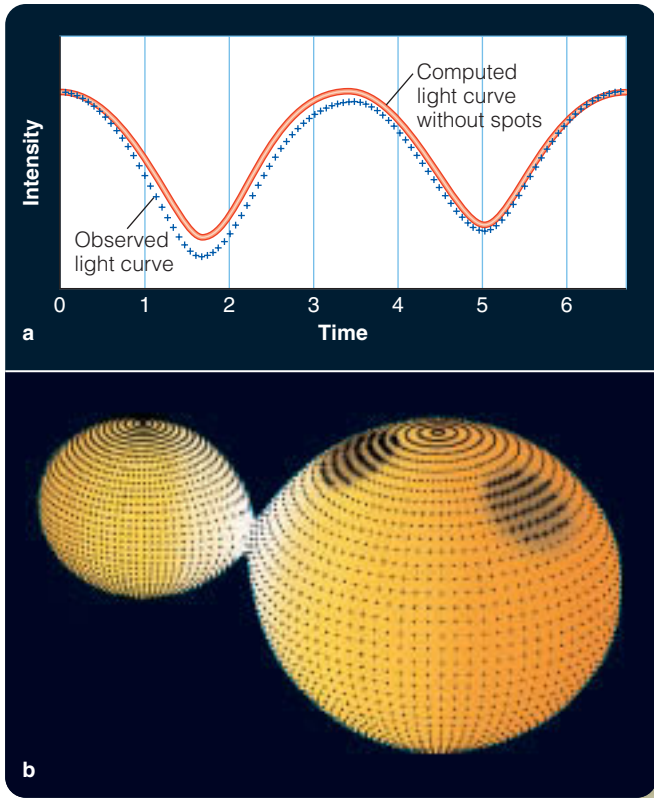


■ **Figure 9-20**

From Earth, an eclipsing binary looks like a single point of light, but changes in brightness reveal that two stars are eclipsing each other. Doppler shifts in the spectrum combined with the light curve, shown here as magnitude versus time, can reveal the size and mass of the individual stars.

two stars. You can find the true orbital velocity because you don't have to untip the orbits; you know they are nearly edge-on or there would not be eclipses. Then you can find the size of the orbits and the masses of the stars.

Earlier in this chapter you used luminosity and temperature to find the radii of stars, but eclipsing binary systems provide a way

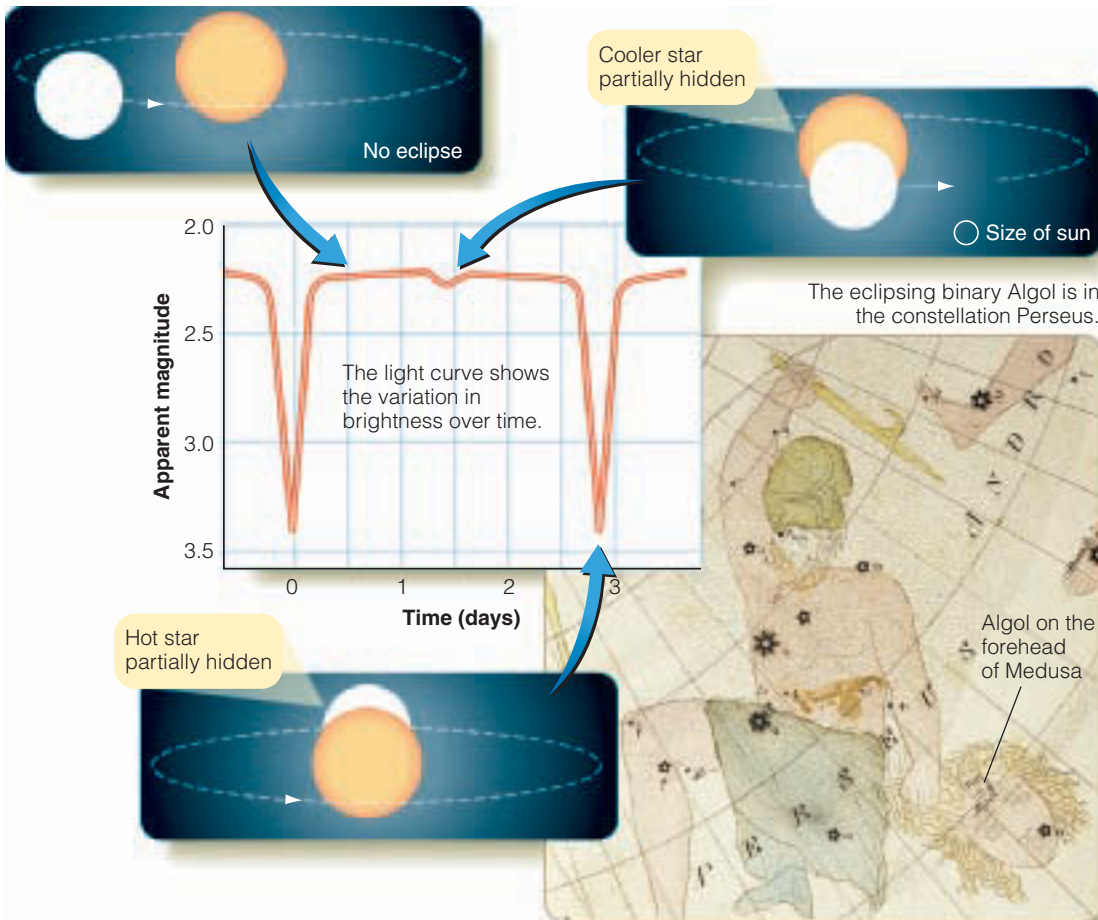


■ **Figure 9-21**

The observed light curve of the binary star VW Cephei (lower curve) shows that the two stars are so close together their gravity distorts their shapes. Slight distortions in the light curve reveal the presence of dark spots at specific places on the star's surface. The upper curve shows what the light curve would look like if there were no spots. (Graphics created with Binary Maker 2.0)

to measure the sizes of stars directly. From the light curve you can tell how long it takes for the small star to cross the large star. Multiplying this time interval by the orbital velocity of the small star gives the diameter of the larger star. You can also determine the diameter of the small star by noting how long it takes to disappear behind the edge of the large star. For example, if it takes 300 seconds for the small star to disappear while traveling 500 km/s relative to the large star, then it must be 150,000 km in diameter.

Algol (β Persei) is one of the best-known eclipsing binaries because its eclipses are visible to the naked eye. Normally, its magnitude is about 2.15, but its brightness drops to 3.4 during eclipses that occur every 68.8 hours. Although the nature of the star was not recognized until 1783, its periodic dimming was probably known to the ancients. *Algol* comes from the Arabic for “the demon,” and it is associated in constellation mythology with the severed head of Medusa, the sight of whose serpentine locks turned mortals to stone (■ Figure 9-22). Indeed, in some accounts, Algol is the winking eye of the demon.



■ **Figure 9-22**

The eclipsing binary Algol consists of a hot B star and a cooler G or K star. The eclipses are partial, meaning that neither star is completely hidden during eclipses. The orbit here is drawn as if the cooler star were stationary.

Basic Scientific Data

Where do large masses of scientific data come from? In a simple sense, science is the process by which scientists look at data and search for relationships, and it sometimes requires large amounts of data. For example, astronomers need to know the masses and luminosities of many stars before they can begin to understand the mass–luminosity relationship.

Compiling basic data is one of the common forms of scientific work—a necessary first step toward scientific analysis and understanding. An archeologist may spend months or even years diving to the floor of the Mediterranean Sea to study an ancient Greek shipwreck. She will carefully measure the position of every wooden timber and bronze fitting. She will photograph and recover everything from broken pottery to tools and weapons. The care with which she records data on the site pays

off when she begins her analysis. For every hour the archaeologist spends recovering an object, she may spend days or weeks in her office, a library, or a museum identifying and understanding the object. Why was there a Phoenician hammer on a Greek ship? What does that reveal about the economy of ancient Greece?

Finding, identifying, and understanding that ancient hammer contributes only a small bit of information, but the work of many scientists eventually builds a picture of how ancient Greeks saw their world. Solving a single binary star system to find the masses of the stars does not tell an astronomer a great deal about nature. Over the years, however, many astronomers have added their results to the growing data file on stellar masses. Scientific data accumulate and can be analyzed by later generations of scientists.



Collecting mineral samples can be hard work, but it is also fun. Scientists sometimes collect large amounts of data because they enjoy the process. (M. Seeds)

From the study of binary stars, astronomers have found that the masses of stars range from roughly 0.1 solar mass at the low end to over 100 solar masses at the high end. The most massive star ever found in a binary system has a mass of about 115 solar masses and orbits a companion star that is nearly as massive. A few other stars are believed to be more massive up to about 150 solar masses, but they do not lie in binary systems, so astronomers must estimate their mass.

SCIENTIFIC ARGUMENT

When you look at the light curve for an eclipsing binary system with total eclipses, how can you tell which star is hotter?

A good scientific argument is a chain of inference with no missing links. Start by assuming that the two stars in an eclipsing binary system are not the same size; then you can refer to them as the larger star and the smaller star. When the smaller star moves behind the larger star, you lose the light coming from the total area of the small star. And when the smaller star moves in front of the larger star, it blocks off light from the same amount of area on the larger star. In both cases, the same area, the same number of square meters, is hidden from your sight. That means the amount of light lost during an eclipse depends only on the temperature of the hidden surface because temperature is what determines how much a single square meter can radiate per second. When the surface of the hotter star is hidden, the brightness will fall dramatically, but when the surface of the cooler star is hidden, the brightness will not fall as much. So you can look at the light curve and point to the deeper of the two eclipses and say, “That is where the hotter star is behind the cooler star.”

Now change the argument to consider the diameters of the stars. **How could you look at the light curve of an eclipsing binary with total eclipses and find the ratio of the diameters?**

9-5 A Census of the Stars

YOU HAVE LEARNED how to find the luminosities, diameters, and masses of stars, and now you can put all those data together (**How Do We Know? 9-2**) to paint a family portrait of the stars. As in any family portrait, both similarities and differences are important clues to the history of the family. As you begin trying to understand how stars are born and how they die, ask a simple question: What is the average star like? Answering that question is both challenging and illuminating.

Surveying the Stars

If you want to know what the average person thinks about a certain subject, you take a survey. If you want to know what the average star is like, you must survey the stars. Such surveys reveal important relationships among the family of stars.

Not many decades ago, surveying large numbers of stars was an exhausting task, but modern computers have changed that. Specially designed telescopes controlled by computers can make millions of observations per night, and high-speed computers can compile these data into easy-to-use databases. Those surveys produce mountains of data that astronomers can mine while searching for relationships within the family of stars.

The Family of Stars

1 What is the most common kind of star? Are some rare? Are some common? To answer those questions you must survey the stars. To do so you must know their spectral class, their luminosity class, and their distance. Your census of the family of stars produces some surprising demographic results.

1a You could survey the stars by observing every star within 62 pc of Earth. A sphere 62 pc in radius encloses a million cubic parsecs. Such a survey would tell you how many stars of each type are found within a volume of a million cubic parsecs.



2 Your survey faces two problems.

1. The most luminous stars are so rare you find few in your survey region. There are no O stars at all within 62 pc of Earth.
2. Lower-main-sequence M stars, called red dwarfs, and white dwarfs are so faint they are hard to locate even when they are only a few parsecs from Earth. Finding every one of these stars in your survey sphere is a difficult task.

Spectral Class Color Key

- O and B
- A
- F
- G
- K
- M

The star chart in the background of these two pages shows most of the constellation Canis Major; stars are represented as dots with colors assigned according to spectral class. The brightest stars in the sky tend to be the rare, highly luminous stars, which look bright even though they are far away. Most stars are of very low luminosity, so nearby stars tend to be very faint red dwarfs.

η Canis Majoris
B5Ia 980 pc

δ Canis Majoris
F8Ia 550 pc

ϵ Canis Majoris
B2II 130 pc

Red dwarf
15 pc

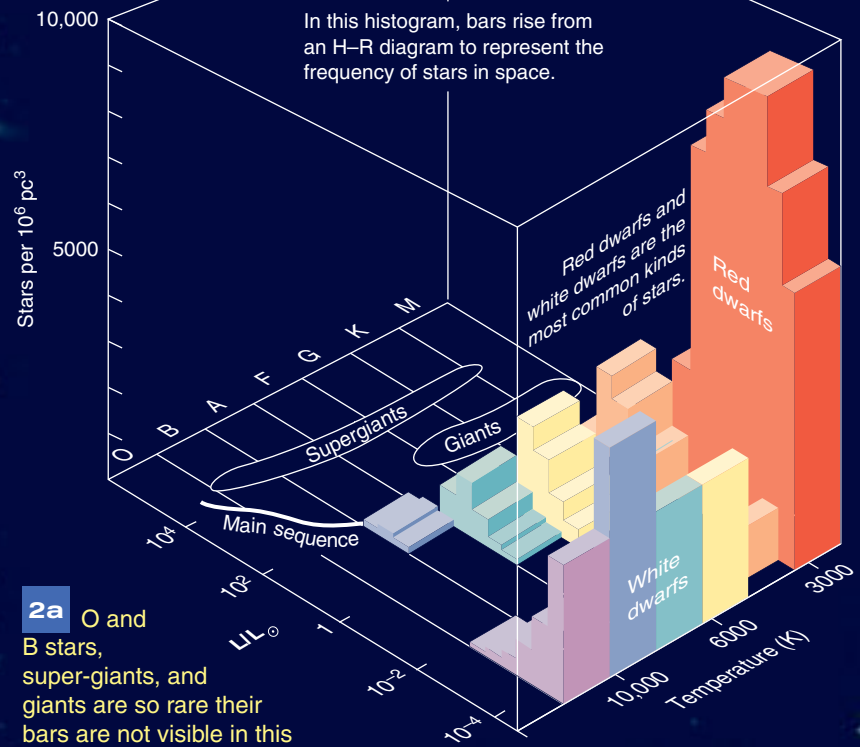
σ^2 Canis Majoris
B3Ia 790 pc

Red dwarf
17 pc

σ Canis Majoris
M0Iab 370 pc

Sirius A (α Canis Majoris) is the brightest star in the sky. With a spectral type of A1V, it is not a very luminous star. It looks bright because it is only 2.6 pc away.

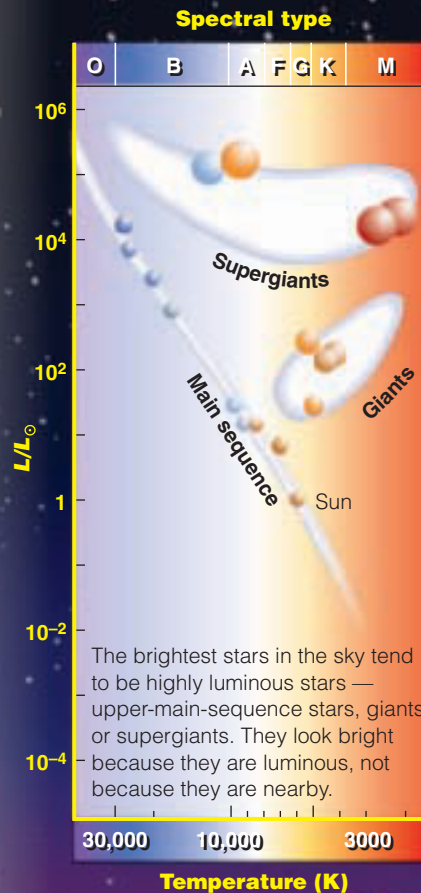
Sirius B is a white dwarf that orbits Sirius A. Although Sirius B is not very far away, it is much too faint to see with the unaided eye.



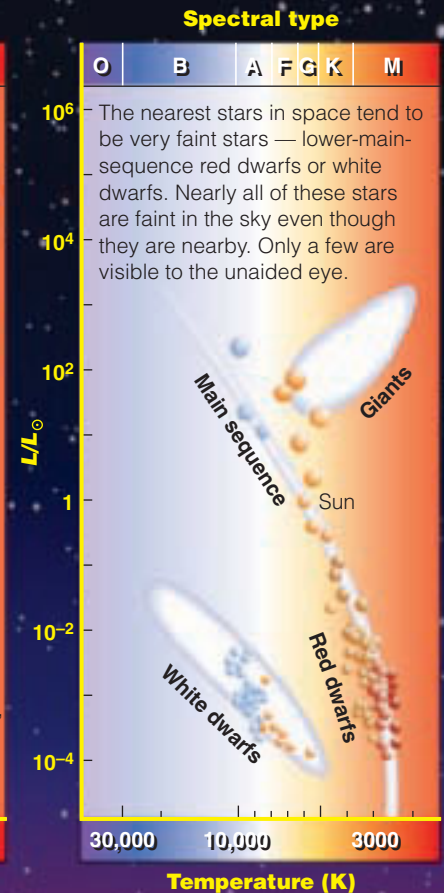
2a O and B stars, supergiants, and giants are so rare their bars are not visible in this graph.

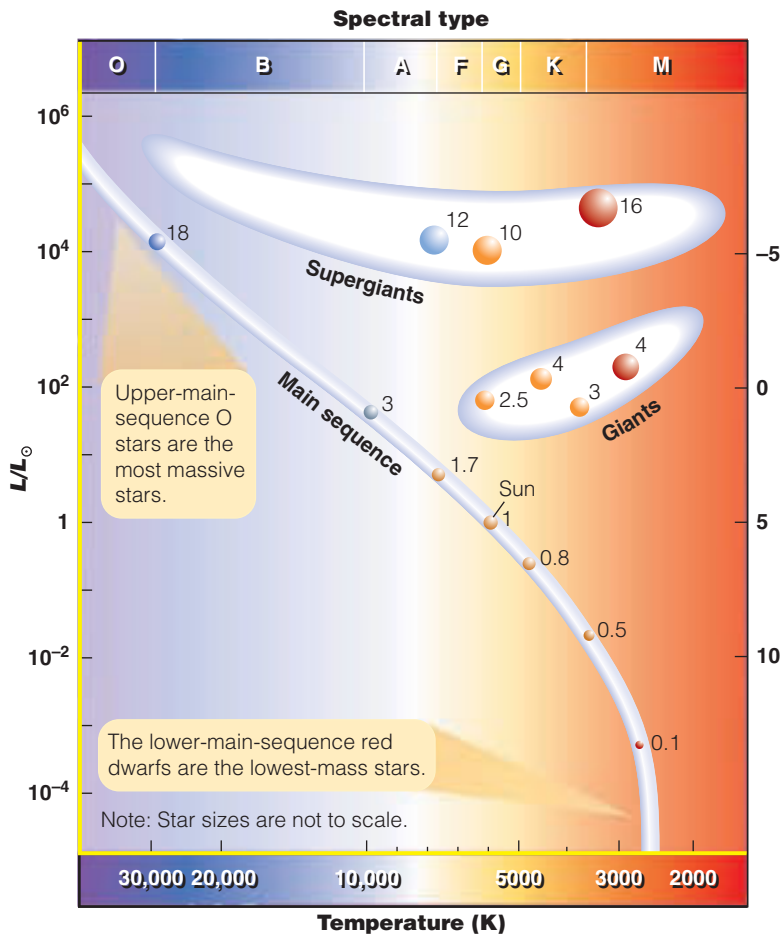
3 Luminous stars are rare but are easy to see. Most stars are very low luminosity objects. Not a single white dwarf or red dwarf is bright enough to see with the unaided eye. See H-R diagrams at right.

Brightest stars



Nearest stars





■ **Figure 9-23**

The masses of the plotted stars are labeled on this H-R diagram. Notice that the masses of main-sequence stars decrease from top to bottom but that masses of giants and supergiants are not arranged in any ordered pattern.

Mass, Luminosity, and Density

If you survey enough stars and plot the data in an H-R diagram, you can see the patterns that hint at how stars are born, how they age, and how they die.

If you label an H-R diagram with the masses of the plotted stars, as in ■ Figure 9-23, you will discover that the main-sequence stars are ordered by mass. The most massive main-sequence stars are the hot stars, and as you run your eye down the main sequence, you will find successively lower-mass stars, until you reach the lowest-mass, coolest, faintest main-sequence stars.

Stars that do not lie on the main sequence are not in order according to mass. Giant stars are a jumble of different masses, and supergiants, although they tend to be more massive than giants, are in no particular order in the H-R diagram. In contrast, all white dwarfs have about the same mass, somewhere in the narrow range of from 0.5 to about 1 solar mass.

Because of the systematic ordering of mass along the main sequence, the main-sequence stars follow a **mass–luminosity relation**—the more massive a star is, the more luminous it is (■ Figure 9-24). In fact, the mass–luminosity relation can be expressed as a simple formula:

$$L = M^{3.5}$$

That is, a star's luminosity (in terms of the sun's luminosity) equals its mass (in solar masses) raised to the 3.5 power. For example, a star of 4 solar masses has a luminosity of approximately $4^{3.5}$, which equals $4 \times 4 \times 4 \times \sqrt{4}$. This equals 64×2 , or 128. So a 4-solar-mass star will have a luminosity of about 128 times the luminosity of the sun. This is only an approximate equation, as shown by the red line in Figure 9-24.

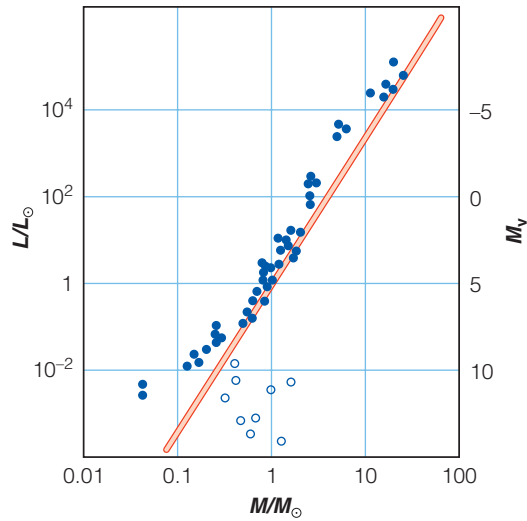
Notice how large the range in luminosity is. The observed range of stellar masses extends from about 0.08 solar mass to over 100 solar masses—a factor of roughly 1000. But the range of luminosities extends from about 10^{-6} to about 10^6 solar luminosities—a factor of a trillion (10^{12}). Clearly, a small difference in mass causes a large difference in luminosity.

Although giants and supergiants do not follow the mass–luminosity relation very closely, and white dwarfs do not follow it at all, the link between mass and luminosity is critical in astronomy. In the next chapter, the mass–luminosity relation will help you understand how stars generate their energy.

What could you learn about stars from a survey of the stars near the sun? Because the sun is thought to be in a typical place in the universe, such a survey could reveal general characteristics of stars everywhere, and might reveal unexpected processes governing the formation and evolution of stars. Study **The Family of Stars** on pages 186–187 and notice three important points:

- 1 Taking a survey is difficult because you must be sure you get an honest sample. If you don't survey enough stars, or if you don't notice some kinds of stars, you can get biased results.
- 2 Most stars are faint, and luminous stars are rare. The most common kinds of stars are the lower-main-sequence red dwarfs and the white dwarfs.
- 3 A survey reveals that what you see in the sky is deceptive. Stars near the sun are quite faint; but luminous stars, although they are rare, are easily visible even at great distances. Many of the brighter stars in the sky are highly luminous stars that you see even though they are far away.

The night sky is a beautiful carpet of stars, but they are not all the same. Some are giants and supergiants, and some are dwarfs.



■ **Figure 9-24**

The mass–luminosity relation shows that the more massive a main-sequence star is, the more luminous it is. The open circles represent white dwarfs, which do not obey the relation. The red line represents the equation $L = M^{3.5}$.

The density of stars reveals another pattern in the H–R diagram. The average density of a star is its mass divided by its volume. Stars are not uniform in density but are most dense at their centers and least dense near their surface. The center of the sun, for instance, is about 100 times as dense as water; its density near the visible surface is about 3400 times less dense than Earth’s atmosphere at sea level. A star’s average density is intermediate between its central and surface densities. The sun’s average density is approximately 1 g/cm^3 —about the density of water.

Main-sequence stars have average densities similar to the sun’s, but giant stars, being large, have low average densities, ranging from 0.1 to 0.01 g/cm^3 . The enormous supergiants have still lower densities, ranging from 0.001 to 0.000001 g/cm^3 .

These densities are thinner than the air you breathe, and if you could insulate yourself from the heat, you could fly an airplane through these stars. Only near the center would you be in any danger, for there the material is very dense—roughly three million times the density of water.

The white dwarfs have masses about equal to the sun’s but are very small, only about the size of Earth. That means the matter is compressed to enormous densities. On Earth, a teaspoonful of this material would weigh about 15 tons.

Density divides stars into three groups. Most stars are main-sequence stars with densities like the sun’s. Giants and supergiants are very-low-density stars, and white dwarfs are high-density stars. You will see in later chapters that these densities reflect different stages in the evolution of stars.

SCIENTIFIC ARGUMENT

What kind of stars do you see if you look at a few of the brightest stars in the sky?

This argument shows how careful you must be to interpret simple observations. When you look at the night sky, the brightest stars are mostly giants and supergiants. Most of the bright stars in Canis Major, for instance, are supergiants. Sirius, one of your Favorite Stars, is an exception. It is the brightest star in the sky, but it is just a main-sequence star that looks bright because it is very nearby, not because it is very luminous. In general, the supergiants and giants are so luminous that they stand out and look bright, even though they are not nearby. When you look at a bright star in the sky, you are probably looking at a highly luminous star—a supergiant or a giant. You can check this argument above by consulting the tables of the brightest and nearest stars in the Appendix.

Now revise your argument. **What kinds of stars do you see if you look at the stars nearest to the sun?**

What Are We? Medium

We humans are medium creatures, and we experience medium things. You can see trees and flowers and small insects, but you cannot see the beauty of the microscopic world without ingenious instruments and special methods. Similarly, you can sense the grandeur of a mountain range, but larger objects, such as stars, are too big for our medium senses. You have to use your ingenuity and imagination to experience the truth of such large objects. That is what science does for us. We live between the microscopic world and the

astronomical world, and science enriches our lives by revealing the parts of the universe beyond our daily experience.

Experience is fun, but it is very limited. You may enjoy experiencing a flower by admiring its color and shape and by smelling its fragrance. But the flower is more wonderful than your experience can reveal. To truly appreciate the flower you need to understand it—how it serves its plant and how the plant came to create such a beautiful blossom.

Humans have a natural drive to understand as well as experience. You have experienced the stars in the night sky, and now you are beginning to understand them as objects ranging from hot blue O stars to cool red M dwarfs. It is natural for you to wonder why these stars are so different. As you explore that story in the following chapters, you will discover that although you have medium senses, you can understand the stars.

Study and Review

Summary

- ▶ Your goal in this chapter was to characterize the stars by finding their luminosities, diameters, and masses. Before you could begin, you needed to find their distances. Only by first knowing the distance to a star could you find its other properties.
- ▶ Astronomers can measure the distance to nearer stars by observing their **stellar parallaxes (p)** (p. 169). The most distant stars are so far away that their parallaxes are unmeasurably small. Space telescopes above Earth's atmosphere have measured the parallaxes of a huge number of stars.
- ▶ Stellar distances are commonly expressed in **parsecs (p. 169)**. One parsec is 2.06×10^5 AU—the distance to an imaginary star whose parallax is 1 arc second. One parsec equals 3.26 light-years.
- ▶ **Proper motions (p. 170)** can give you a clue to distance because nearby stars tend to have large proper motions.
- ▶ The amount of light received from a star, the **light flux (p. 171)**, is related to its distance by the inverse square law. Once you know the distance to a star, you can use the **magnitude–distance formula (p. 172)** to find its **intrinsic brightness (p. 171)** expressed as its **absolute visual magnitude (M_v) (p. 171)**—the apparent magnitude the star would have if it were 10 pc away. A star's **distance modulus (p. 172)** is the difference between its apparent and absolute magnitudes.
- ▶ To find the energy output of a star, astronomers must correct for the light at wavelengths that are not visible to convert absolute visual magnitude into **absolute bolometric magnitude (p. 172)**, which can be converted into **luminosity (L) (p. 172)**, the total energy radiated by the star in one second.
- ▶ The **Hertzsprung–Russell (H–R) diagram (p. 174)** is a plot of luminosity versus surface temperature. It is an important graph in astronomy because it sorts the stars into categories by size.
- ▶ Roughly 90 percent of normal stars, including the sun, fall on the **main sequence (p. 175)**, with the more massive stars being hotter and more luminous. The **giants (p. 175)** and **supergiants (p. 175)**, however, are much larger and lie above the main sequence.
- ▶ **Red dwarfs (p. 175)** lie at the bottom end of the main sequence. Some of the **white dwarfs (p. 175)** are very hot stars, but they fall below the main sequence because they are so small.
- ▶ Observations made with interferometers confirm the sizes of stars implied by the H–R diagram and reveal that rapidly rotating stars are slightly flattened.
- ▶ The large sizes of the giants and supergiants mean their atmospheres have low densities and their spectra have sharper spectral lines than the spectra of main-sequence stars. In fact, it is possible to assign stars to **luminosity classes (p. 176)** by the widths of their spectral lines. Class V stars are main-sequence stars. Giant stars, class III, have sharper lines, and supergiants, class I, have extremely sharp spectral lines.
- ▶ Astronomers can use the locations of the luminosity classes in the H–R diagram to estimate the distances to stars in a technique called **spectroscopic parallax (p. 178)**.
- ▶ The only direct way to find the mass of a star is by studying **binary stars (p. 178)**. When two stars orbit a common center of mass, astronomers find their masses by observing the period and sizes of their orbits. In a **visual binary (p. 180)**, both stars are visible and the orbits can be mapped, but in a **spectroscopic binary (p. 180)** the stars are so close together they look like a single point of light, and the orbits can't be observed directly. Because the inclination of the orbit can't be found, spectroscopic binaries yield only a lower limit to the masses of the stars.
- ▶ In an **eclipsing binary (p. 183)**, the orbits are edge-on, and the stars cross in front of each other. The resulting brightness changes in the

light curve (p. 183) can reveal the diameters of the stars as well as their masses.

- ▶ A survey in the neighborhood of the sun shows that lower-main-sequence stars are the most common type. Giants and supergiants are rare, but white dwarfs are fairly common, although they are faint and hard to find.
- ▶ The **mass–luminosity relation (p. 188)** says that the more massive a star is, the more luminous it is. Main-sequence stars follow this rule closely, the most massive being the upper-main-sequence stars and the least massive the lower-main-sequence stars. Giants and supergiants do not follow the relation precisely, and white dwarfs not at all.
- ▶ Given the mass and diameter of a star, you can find its average density. On the main sequence, the stars are about as dense as the sun, but the giants and supergiants are very-low-density stars. Some are much thinner than air. The white dwarfs, lying below the main sequence, are tremendously dense.

Review Questions

1. Why are Earth-based parallax measurements limited to the nearest stars?
2. Why was the Hipparcos satellite able to make more accurate parallax measurements than ground-based telescopes?
3. What do the words *absolute* and *visual* mean in the definition of absolute visual magnitude?
4. What does luminosity measure that is different from what absolute visual magnitude measures?
5. Why does the luminosity of a star depend on both its radius and its temperature?
6. How can you be sure that giant stars really are larger than main-sequence stars?
7. What evidence shows that white dwarfs must be very small?
8. What observations would you make to classify a star according to its luminosity? Why does that method work?
9. Why does the orbital period of a binary star depend on its mass?
10. What observations would you make to study an eclipsing binary star?
11. Why don't astronomers know the inclination of a spectroscopic binary? How do they know the inclination of an eclipsing binary?
12. How do the masses of stars along the main sequence illustrate the mass–luminosity relation?
13. Why is it difficult to find out how common the most luminous stars are? The least luminous stars?
14. What is the most common kind of star?
15. If you look only at the brightest stars in the night sky, what kind of star are you likely to be observing? Why?
16. **How Do We Know?** What is the missing link in the chain of inference leading from observations of spectroscopic binaries to the masses of the stars?
17. **How Do We Know?** In what way is basic scientific data cumulative, and how do accumulations of such data help later scientists?

Discussion Questions

1. If someone asked you to compile a list of the nearest stars to the sun based on your own observations, how would you select your sample, what measurements would you make, and how would you analyze the measurements to detect nearby stars?
2. The sun is sometimes described as an average star. Is that true? What is the average star really like?

Problems

1. If a star has a parallax of 0.050 arc second, what is its distance in pc? In ly? In AU?
2. If a star has a parallax of 0.016 arc second and an apparent magnitude of 6, how far away is it, and what is its absolute magnitude?
3. Complete the following table:

m	M_v	$d(\text{pc})$	p (arc seconds)
—	7	10	—
11	—	1000	—
—	-2	—	0.025
4	—	—	0.040

4. If a main-sequence star has a luminosity of $400 L_{\odot}$, what is its spectral type? (*Hint*: See Figure 9-13.)
5. If a star has an apparent magnitude equal to its absolute magnitude, how far away is it in parsecs? In light-years?
6. If a star has an absolute bolometric magnitude that is eight magnitudes brighter than the sun, what is the star's luminosity?
7. If a star has an absolute bolometric magnitude that is one magnitude fainter than the sun, what is the star's luminosity?
8. An O8 V star has an apparent magnitude of +1. Use the method of spectroscopic parallax to estimate the distance to the star.
9. Find the luminosity of the sun, given the radius of Earth's orbit and the solar constant (Chapter 8). Make your calculation in two steps. First, use $4\pi R^2$ to calculate the surface area (in square meters) of a sphere surrounding the sun with a radius of 1 AU. Second, multiply by the solar constant to find the total solar energy passing through the sphere in 1 second. That is the luminosity of the sun. Compare your result with that in Celestial Profile 1.
10. In the following table, which star is brightest in apparent magnitude? Most luminous in absolute magnitude? Largest? Farthest away?

Star	Spectral Type	m_v
a	G2 V	5
b	B1 V	8
c	G2 Ib	10
d	M5 III	19
e	White dwarf	15

11. What is the total mass of a visual binary system if its average separation is 8 AU and its period is 20 years?
12. Measure the wavelengths of the iron lines in Figure 9-16 and plot a graph showing the radial velocities of the two stars in this system. What is the period? Assuming that the orbit is circular and edge-on, what is the total mass? What are the individual masses?
13. If the eclipsing binary in Figure 9-20 has a period of 32 days, an orbital velocity of 153 km/s, and an orbit that is nearly edge on, what is the circumference of the orbit? The radius of the orbit? The mass of the system?
14. If the orbital velocity of the eclipsing binary in Figure 9-20 is 153 km/s and the smaller star becomes completely eclipsed in 2.50 hours, what is its diameter?
15. What is the luminosity of a 4-solar-mass main-sequence star? Of a 9-solar-mass main-sequence star? Of a 7-solar-mass main-sequence star?

Learning to Look

1. Look at Figure 9-6. Why is the lava nearest the source brighter and yellower than the lava that is farther away?
2. If all of the stars in the photo here are members of the same star cluster, then they all have about the same distance. Then why are three of the brightest much redder than the rest? What kind of star are they?



NASA

10

The Interstellar Medium



Visual wavelength image

Guidepost

You have begun your study of the sun and other stars, but now it is time to study the thin gas and dust that drifts through space between the stars. This chapter will show you how important this material is to the story of stars and will help you answer three essential questions:

— **How do astronomers study the gas and dust between the stars?**

— **What kinds of material make up the interstellar medium?**

— **How does the matter between the stars interact with the stars?**

The gas and dust between the stars is the starting point for the life story of the stars. The next four chapters will trace the birth, life, and death of stars.

Some 7500 ly from Earth and over 200 ly across, the Eta Carinae Nebula is a churning cloud of gas and dust illuminated by massive newborn stars. The red-purple color is typical of excited hydrogen atoms, but helium and heavier atoms are also present. (ESO)

when he shall die,
Take him and cut him out in little stars,
And he will make the face of heaven so fine
That all the world will be in love with night,
And pay no worship to the garish sun.

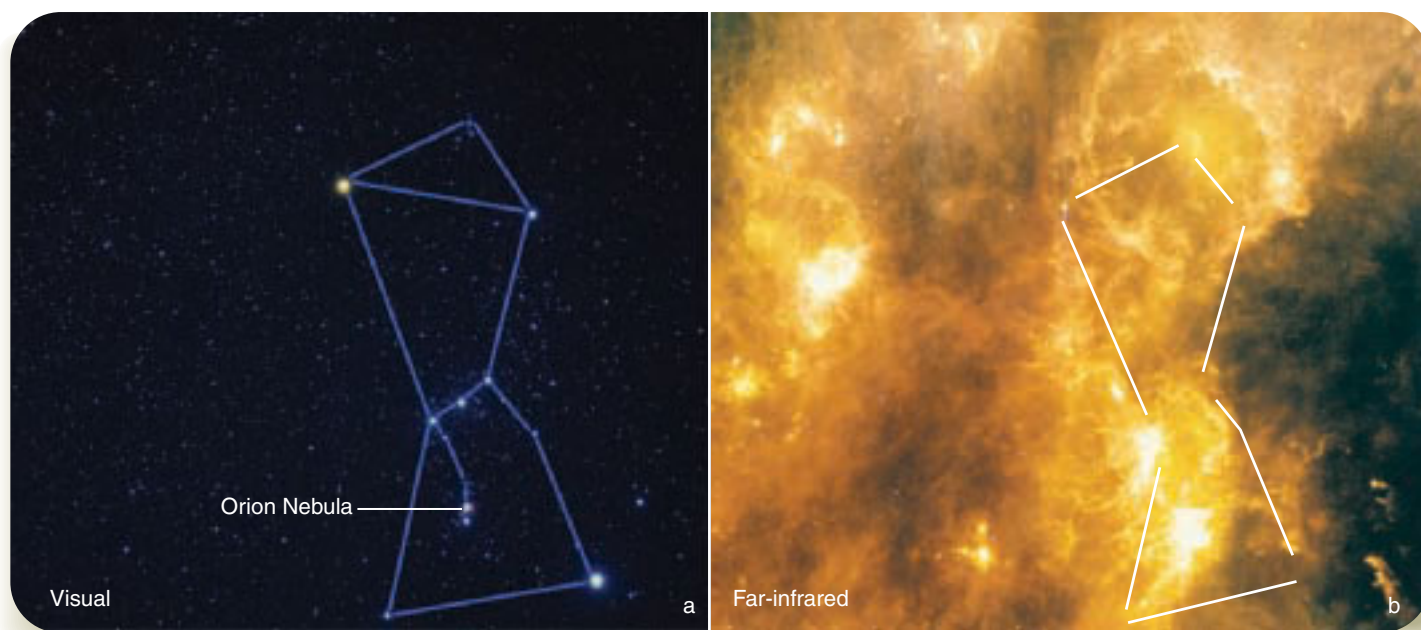
— WILLIAM SHAKESPEARE, *ROMEO AND JULIET*, 3.2.21

JULIET LOVED ROMEO so much she compared him to the beauty of the stars. Had she known what was between the stars, she might have compared him to that instead. True, the gas and dust between the stars is mostly invisible to human eyes, but when observed at infrared wavelengths it is strikingly beautiful, and its densest clouds are the nurseries where new stars are born. If there is beauty in vast extent and sweeping power, then the gas and dust between the stars, called the **interstellar medium** (abbreviated **ISM**), could steal worship from the garish stars.

When people use the phrase, “the vacuum of space,” they reveal a **Common Misconception** that space is empty. Space is not empty; in fact, you are about to discover that the interstellar medium is both complex and, when observed at the proper wavelengths, quite beautiful (■ Figure 10-1).

■ Figure 10-1

(a) At visual wavelengths, the spaces between the stars in and around the constellation Orion seem empty. (b) An infrared image reveals the swirling clouds of the interstellar medium. (Visual: Akito Fujii; IR: NASA/IPAC courtesy Deborah Levine)



10-1 Studying the Interstellar Medium

THERE IS NOTHING SPECIAL about visible light except that you can see it. Although you begin this chapter with what you see, you will need to use all parts of the electromagnetic spectrum to understand the interstellar medium.

Nebulae

On a cold, clear winter night, Orion hangs high in the southern sky, a large constellation composed of brilliant stars. If you look carefully at Orion’s sword, you will see that one of the stars is a hazy cloud (Figure 2-4). A small telescope reveals even more such clouds of gas and dust scattered around the sky. Astronomers refer to these clouds as **nebulae** (singular, nebula), from the Latin word for mist or cloud. They are visible evidence of an interstellar medium.

Read **Three Kinds of Nebulae** on pages 194–195 and notice three important points and four new terms:

- 1 **HII regions** are clouds of gas ionized by the ultraviolet radiation from nearby hot stars. They are often called *emission nebula* because the ionized hydrogen produces visible-wavelength photons that make the regions glow with a characteristic pink color.
- 2 If nearby stars are not hot enough to ionize the hydrogen in a nebula, it may still be visible to human eyes as a *reflection nebula*, produced when light is scattered by tiny dust specks mixed in with the gas.

Three Kinds of Nebulae

1 **Emission nebulae** are produced when a hot star excites the gas near it to produce an emission spectrum. The star must be hotter than about B1 (25,000 K). Cooler stars do not emit enough ultraviolet radiation to ionize the gas. Emission nebulae have a distinctive pink color produced by the blending of the red, blue, and violet Balmer lines. Emission nebulae are also called **HII regions**, following the custom of naming gas with a roman numeral to show its state of ionization. HI is neutral hydrogen, and HII is ionized.

In an HII region, the ionized nuclei and free electrons are mixed. When a nucleus captures an electron, the electron falls down through the atomic energy levels, emitting photons at specific wavelengths. Spectra indicate that the nebulae have compositions much like that of the sun – mostly hydrogen. Emission nebulae have densities of 100 to 1000 atoms per cubic centimeter, better than the best vacuums produced in laboratories on Earth.

Visual-wavelength image

2 A **reflection nebula** is produced when starlight scatters from a dusty nebula. Consequently, the spectrum of a reflection nebula is just the reflected absorption spectrum of starlight. Gas is surely present in a reflection nebula, but it is not excited to emit photons. See image below.

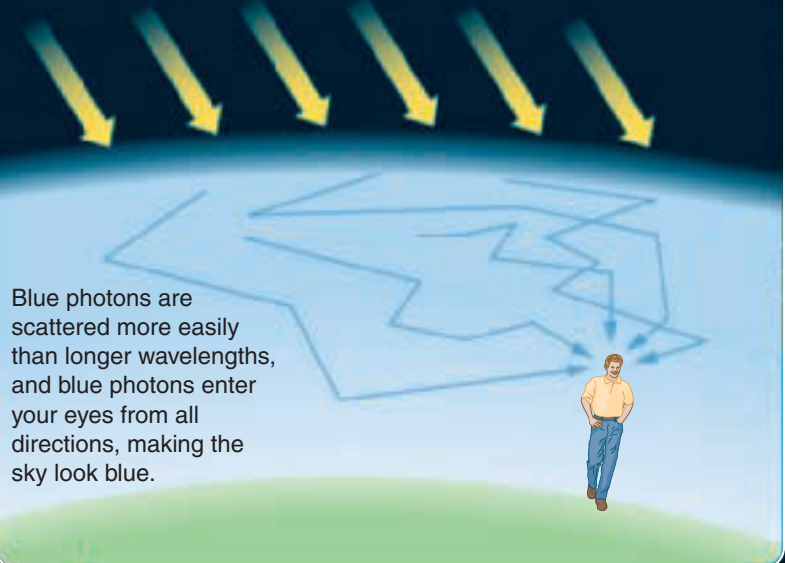
Reflection nebulae NGC 1973, 1975, and 1977 lie just north of the Orion Nebula. The pink tints are produced by ionized gases deep in the nebulae.

Visual-wavelength image

Anglo-Australian Observatory/David Malin Images

2a Reflection nebulae look blue for the same reason the sky looks blue. Short wavelengths scatter more easily than long wavelengths. See image below.

Sunlight enters Earth's atmosphere



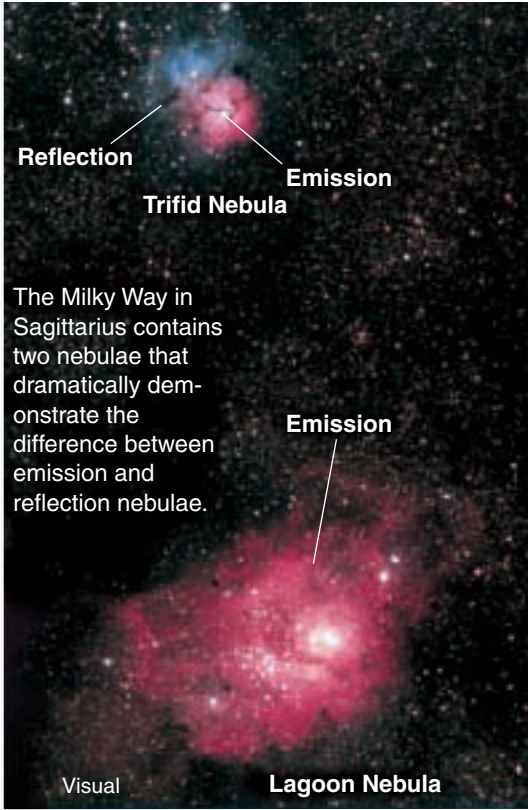
Blue photons are scattered more easily than longer wavelengths, and blue photons enter your eyes from all directions, making the sky look blue.

2b The blue color of reflection nebulae at left shows that the dust particles must be very small in order to preferentially scatter the blue photons. Interstellar dust grains must have diameters ranging from 0.01 μm down to 100 nm or so.

2c In the star cluster called the Pleiades, the hottest stars are B6, not hot enough to ionize hydrogen in the interstellar medium. Instead, the brightest stars produce a reflection nebula as their light is scattered from interstellar dust.



Visual-wavelength image



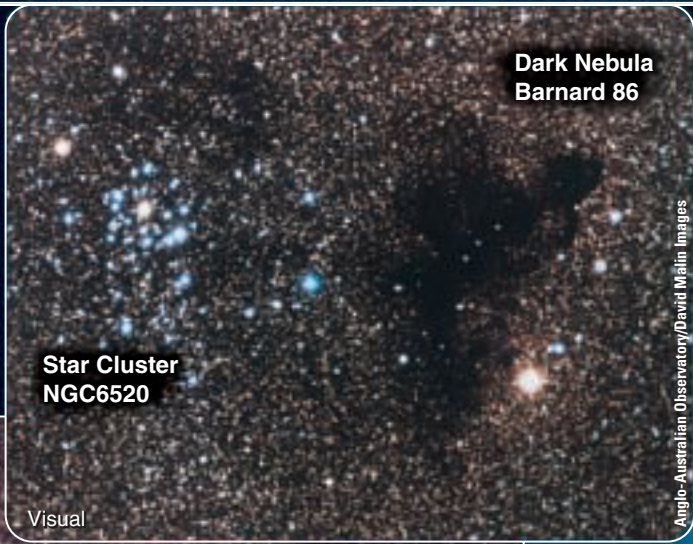
The Milky Way in Sagittarius contains two nebulae that dramatically demonstrate the difference between emission and reflection nebulae.

Visual

Lagoon Nebula

Daniel Good

© Anglo-Australian Observation



Dark Nebula Barnard 86

Star Cluster NGC6520

Visual

Anglo-Australian Observatory/David Malin Images

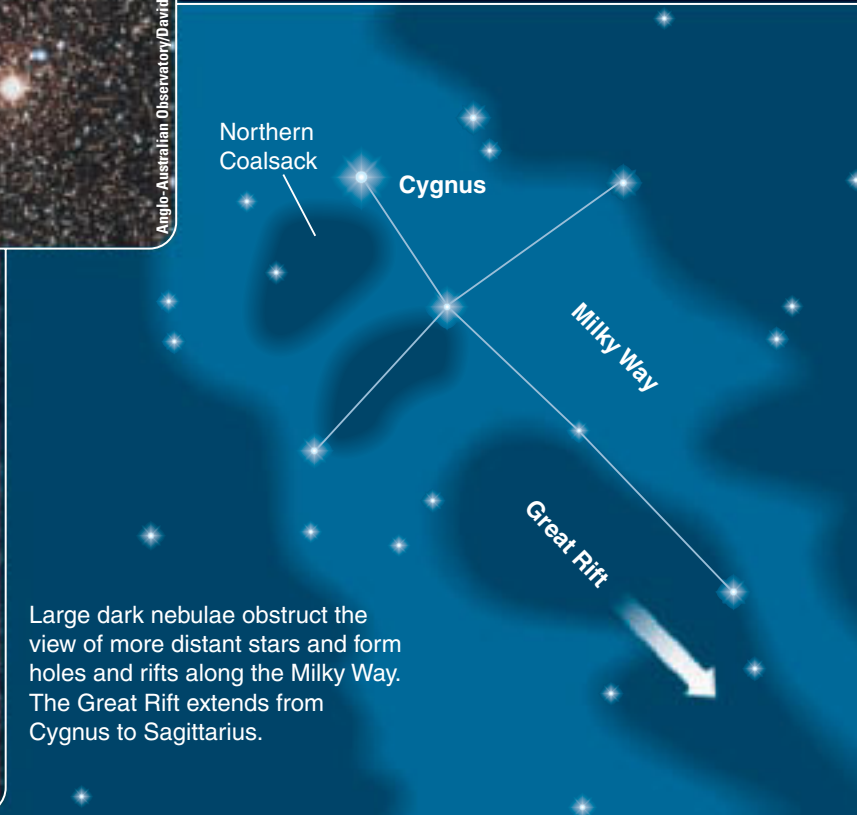
3 **Dark nebulae** are dense clouds of gas and dust that obstruct the view of more distant stars. Some are generally round, but others are twisted and distorted, as shown at the left, suggesting that even when there are no nearby stars to ionize the gas or produce a reflection nebula, there are breezes and currents pushing through the interstellar medium.

Anglo-Australian Observatory/
David Malin Images



Visual-wavelength image

Twisted by intense light from nearby stars, this dark nebula is visible because it obscures more distant stars.



Large dark nebulae obstruct the view of more distant stars and form holes and rifts along the Milky Way. The Great Rift extends from Cygnus to Sagittarius.

3 At visual wavelengths, *dark nebulae* are visible where dense clouds of gas and dust are silhouetted against background regions filled with stars or bright nebulae.

The different kinds of nebulae that decorate the sky are really similar objects seen in different ways much like rain clouds in Earth's atmosphere. On a sunny day, a distant cloud looks white, but overhead it blocks sunlight and looks dark. If you could see the same cloud with infrared eyes, you would see it glowing brightly with blackbody radiation. Different kinds of nebulae are regions of the interstellar medium with different relationships to starlight.

A detailed analysis of the spectra of nebulae can reveal their composition. About 70 percent of the mass in the interstellar medium is hydrogen, 28 percent is helium, and 2 percent is made up of elements heavier than helium. (Look back to Table 7-2 on page 137 and notice this is the same composition as the sun and other stars.) The density of the interstellar medium is very low, typically only 1 atom per cubic centimeter, although it can be much higher in dense clouds. Even in those clouds, the gas is 10^{15} times less dense than the air you breathe.

Almost all of this matter is a thin gas, but about 1 percent of the mass is made up of dust particles called **interstellar dust**. The dust particles are composed of carbon, silicates, iron, and even ice and organic compounds. (An organic compound is made up of molecules that have a carbon chain structure, but it does not have to originate with living things.) The particles are almost all less than 1 micron in diameter. That is only 10^{-6} meters or 1000 nm.

Certain lines in the spectra of emission nebulae are called **forbidden lines** because they are almost never seen in the spectra of excited gas on Earth. This is because transitions between certain energy levels are extremely unlikely. A normal transition might occur after 10^{-8} to 10^{-7} second, but if an electron gets caught in one of these **metastable levels**, it may be stuck for as long as an hour before it falls to a lower level and emits the proper photon. Unless a gas has an extremely low density, collisions between atoms disturb electrons caught in metastable levels long before they can make a transition downward and emit a photon. That means forbidden lines are produced only by very-low-density gas and are generally not visible in laboratories on Earth where gas densities are not low enough. The gases in Earth's upper atmosphere have low enough density to emit forbidden lines visible as aurorae (see Chapter 8).

Even in a denser than average nebula, the gas has a very low density, and an atom could go for an hour or more between collisions, giving an electron stuck in a metastable level time to decay to a lower level and emit a photon at a so-called forbidden wavelength.

Two good examples of forbidden lines are the strong green lines at 495.9 nm and 500.7 nm produced by oxygen atoms that have lost two electrons. (Following the convention for naming ions, twice-ionized oxygen is OIII. Neutral oxygen is symbolized

as OI.) The oxygen ions can become excited by collision with a high-energy photon or a rapidly moving ion or electron, and the atom can emit various-wavelength photons as its electron cascades back down to lower energy levels. Some of those electrons get caught in metastable levels and eventually emit photons at forbidden wavelengths.

The forbidden lines are clear evidence that nebulae have very low densities. This is an example of how astronomers can use knowledge of atomic physics to understand astronomical objects.

Extinction and Reddening

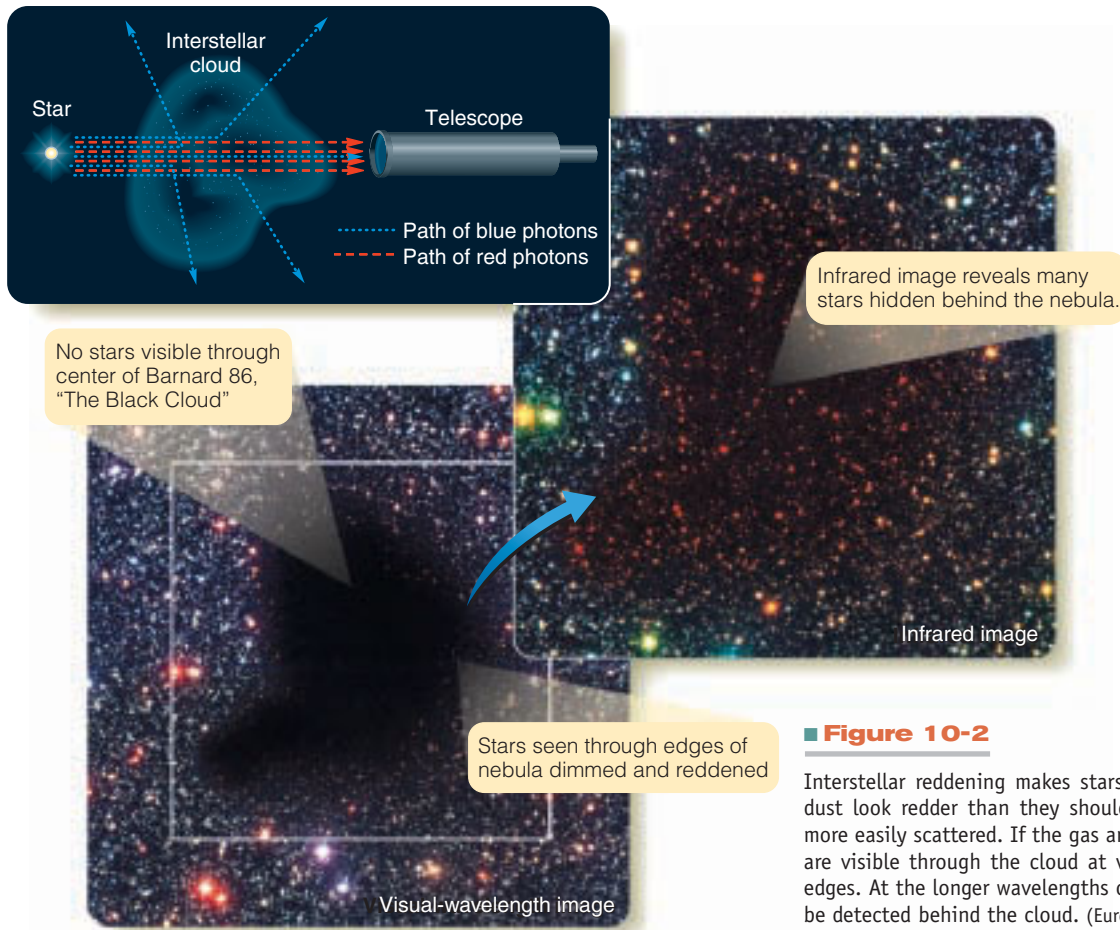
One way to study the interstellar medium is to examine the starlight that passes through it. The interstellar medium makes distant stars appear fainter than they would if space were perfectly transparent. This phenomenon is called **interstellar extinction**, and in the neighborhood of the sun it amounts to about 1 magnitude per thousand parsecs at visual wavelengths. That is, a star 1000 pc from Earth will look about 1 magnitude fainter to human eyes than it would if space were perfectly empty. If it were 2000 pc away, it would look about 2 magnitudes dimmer, and so on. This is a dramatic effect at visual wavelengths, and it shows that the interstellar medium is not confined to a few nebulae scattered here and there. The spaces between the stars are far from empty.

The interstellar medium also affects the colors of stars. As you saw earlier, the dust particles are small, with diameters equal to or smaller than the wavelengths of light, so they scatter shorter wavelengths better than longer wavelengths. That is the reason why extinction is more severe at shorter wavelengths, and that makes stars look redder than they should be, a process called **interstellar reddening** (■ Figure 10-2). Some hot O stars, for instance, look red and not blue because of reddening.

You see reddening when you look at the setting sun. As the sun sets, sunlight must travel through a lot of air on its way to your eyes, and blue photons are more likely to be scattered. A larger proportion of red photons reach your eyes, and the setting sun looks red.

Note that interstellar reddening does not shift the wavelengths of spectral lines as does the Doppler effect. Rather, reddening changes the proportions of long- and short-wavelength photons that reach Earth, and that makes distant stars redder.

Astronomers can measure the amount of reddening by comparing two stars of the same spectral type, one of which is dimmed more than the other. If you plot the difference in brightness between the two stars against wavelength, you get a curve that shows the reddening. That is, it shows how the starlight is dimmed at different wavelengths (■ Figure 10-3). In general, the light is dimmed in proportion to the reciprocal of the wavelength, a pattern typical of scattering from small dust particles. Laboratory measurements suggest that the high extinction at about 220 nm is caused by a spectral feature of one form of carbon, evidence that some of the dust particles contain carbon.



■ **Figure 10-2**

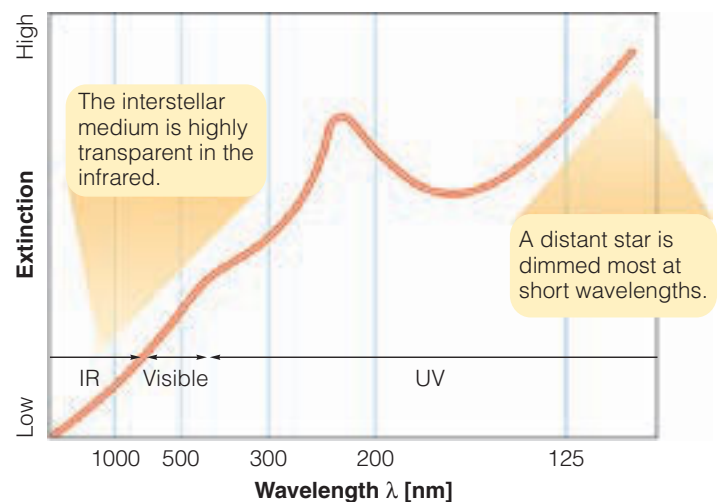
Interstellar reddening makes stars seen through a cloud of gas and dust look redder than they should because shorter wavelengths are more easily scattered. If the gas and dust is especially dense, no stars are visible through the cloud at visual wavelengths except near the edges. At the longer wavelengths of the near-infrared, many stars can be detected behind the cloud. (European Southern Observatory)

In many cases, clouds of interstellar matter are so dense, they block our view at visual wavelengths, and even the less dense parts of the interstellar medium dim starlight severely. Look again at Figure 10-3 and notice how low extinction is in the infrared. The interstellar medium is highly transparent at near-infrared wavelengths (■ Figure 10-4), but at much longer infrared wavelengths, the interstellar medium glows with blackbody radiation emitted by the dust.

Interstellar Absorption Lines

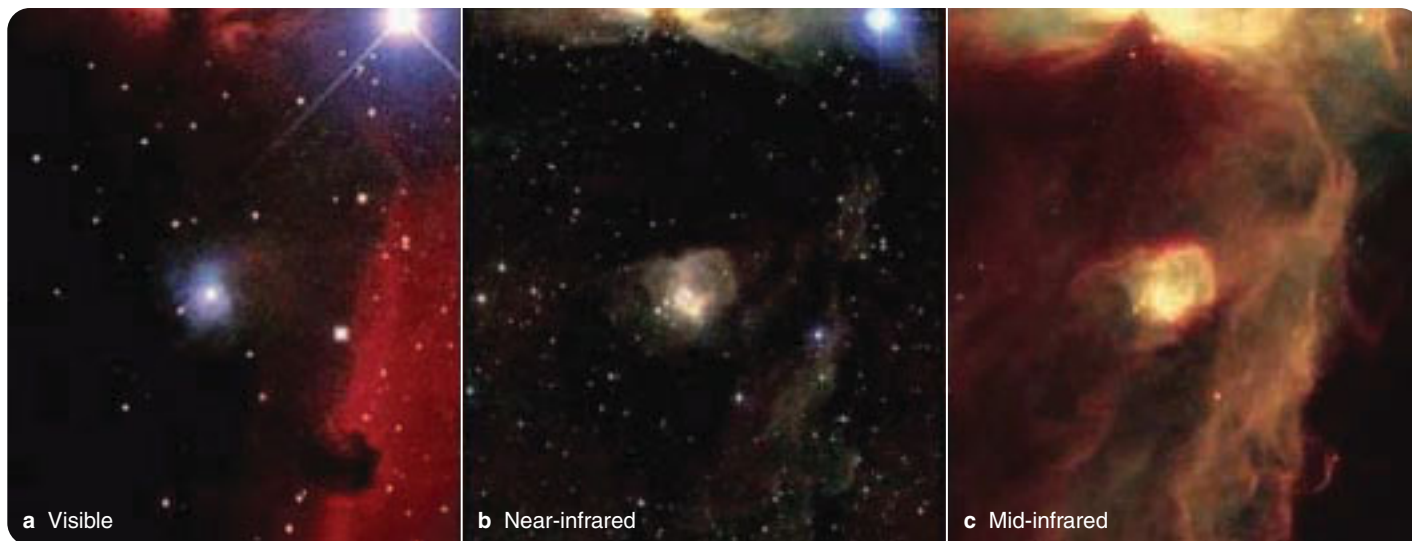
As light travels through the interstellar medium, atoms can absorb specific wavelengths and form **interstellar absorption lines** in the spectra of stars. Astronomers can tell interstellar absorption lines from stellar absorption lines in a number of ways.

Some stellar spectra contain absorption lines that obviously don't belong to the stars because they represent the wrong ionization state. For example, if you looked at the spectrum of a very hot star such as an O star, you would expect to see no lines of once-ionized calcium (Ca II) because that ion cannot exist at the high temperatures found in the atmosphere of such a hot star. But many O-star spectra contain spectral lines of Ca II. These lines must have been produced not in the star's atmosphere but in the interstellar medium between the star and Earth.



■ **Figure 10-3**

Interstellar extinction, the dimming of starlight by dust between the stars, depends strongly on wavelength. Infrared radiation is only slightly affected, but ultraviolet light is strongly scattered. The strong extinction at about 220 nm is caused by a spectral feature of a form of carbon dust in the interstellar medium.

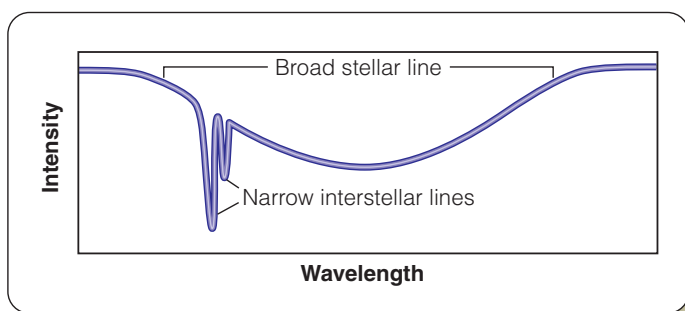


■ **Figure 10-4**

(a) At visual wavelengths, the Horsehead Nebula is a dark nebula extending away from a larger dark cloud. (Howard McCallon) (b) At near-infrared wavelengths, the dark nebulae are nearly transparent, and stars are visible through them. (2MASS) (c) At much longer infrared wavelengths, the clouds glow with blackbody radiation emitted by dust grains. (ISO)

The widths of the interstellar lines also give away their identities. In the atmosphere of a star, the gas is so dense that atoms collide with each other often and disturb the atomic energy levels. That blurs the spectral lines and makes them broader. Also, in a hot gas, the atoms move so rapidly that they produce small Doppler shifts, some red some blue, and that broadens the spectral lines. In contrast, interstellar gas is cold and has a very low density, so atoms collide only rarely. That means interstellar absorption lines are exceedingly sharp (■ Figure 10-5).

Interstellar lines are also found in the spectra of some spectroscopic binary stars (see Chapter 9). As the two stars orbit each other, Doppler shifts move their spectral lines apart, together, and then apart again, but the narrow interstellar lines don't move and are obviously not produced by the stars in the spectroscopic binary.



■ **Figure 10-5**

Interstellar absorption lines can be recognized because they are very narrow. Here a spectral line produced in the atmosphere of a star is so magnified that it is seen as a broad dip in the plot. In contrast, the absorption lines produced by two clouds in the interstellar medium are much narrower.

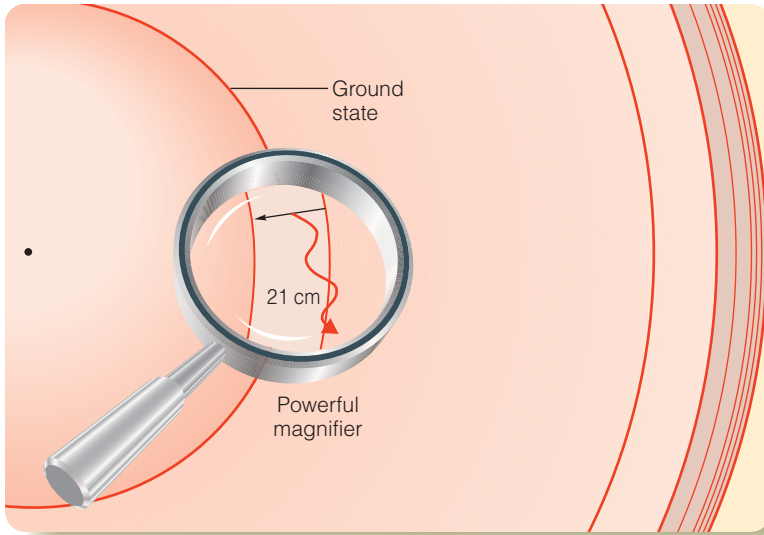
Interstellar lines are often split into two or more components. The multiple components have slightly different wavelengths and must have been produced when the light from the star passed through different clouds of gas on its way to Earth. Because individual clouds of gas have slightly different radial velocities, they produce absorption lines with slightly different Doppler-shifted wavelengths.

Interstellar Emission Lines

You expect from Kirchhoff's second law (Chapter 7) that an excited low-density gas viewed against an empty or colder background should produce an emission spectrum, and the interstellar medium does exactly that. As you also learned via Kirchhoff's laws, the wavelengths of a given atom or molecule's emission lines are the same as the wavelengths of its absorption lines. Emission lines, like absorption lines, give astronomers powerful ways to study the gas and dust between the stars.

For example, cold, neutral hydrogen floating in space can emit electromagnetic radiation with a wavelength of 21 cm, which can be detected with radio telescopes. This **21-cm radiation** is an emission line.

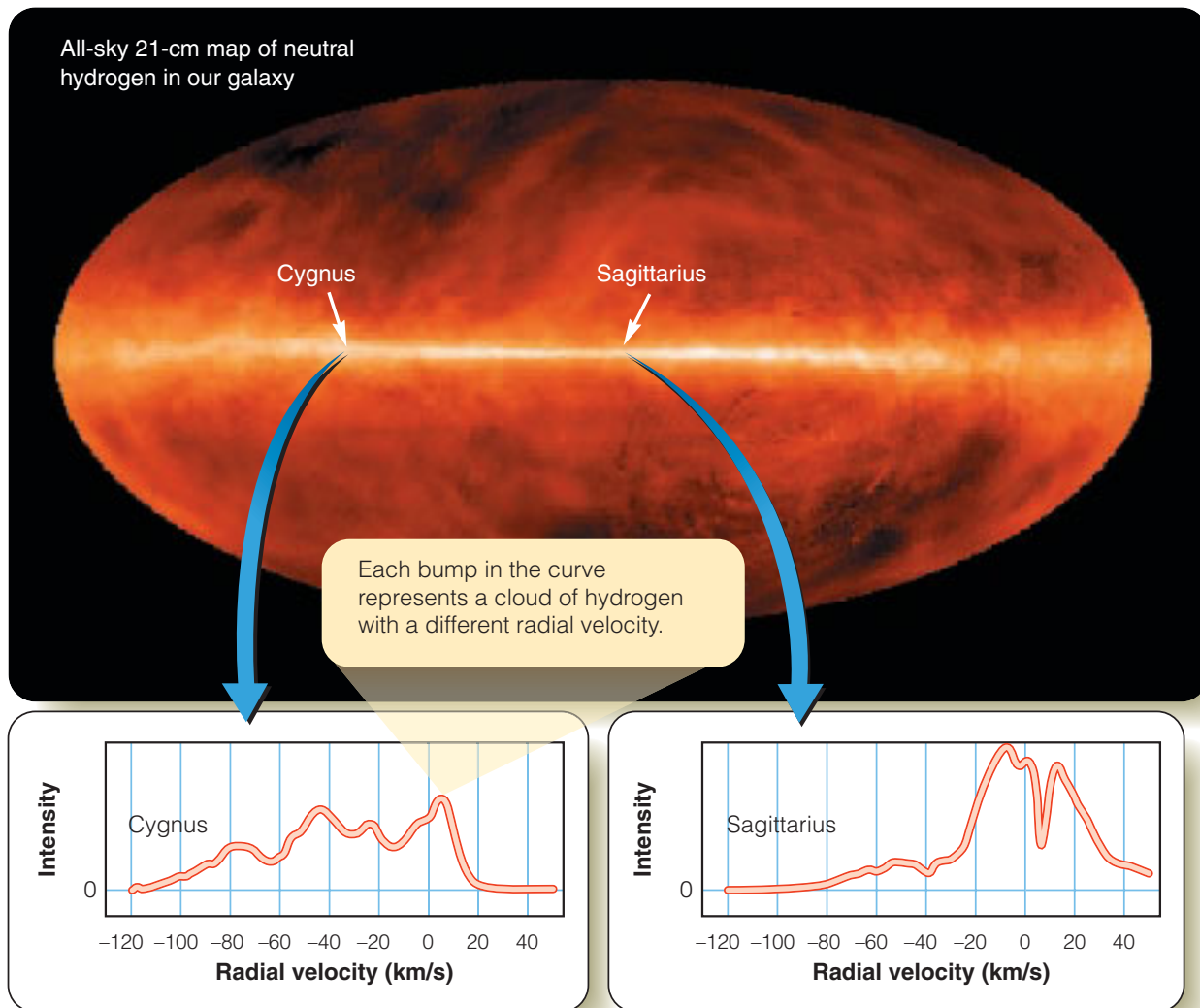
How could cold hydrogen atoms emit radio-wavelength photons? A hydrogen atom consists of an electron and a proton, and they both spin. Because they have electric charges, that spinning generates tiny magnetic fields, and if the two particles spin in the same direction, the magnetic fields are reversed because the particles have opposite charges. If they spin opposite to each other, the magnetic fields are aligned. In cold, unexcited hydrogen there are two ways the electron can settle into the ground state—spinning one way or the other way—and that means the ground state is really two energy levels separated by a tiny amount of energy (■ Figure 10-6). If the electron is spinning one way, it can flip over and spin the other way, releasing the excess energy as a photon with a wavelength of 21 cm.



■ **Figure 10-6**

Because the proton and electron in a hydrogen atom can spin in the same or in the opposite directions, the ground state is actually two closely spaced energy levels. In this diagram, you would need a magnifying glass to distinguish the two levels. When an atom decays from the upper level to the lower level, it emits a photon with a wavelength of 21 cm.

The 21-cm radiation is a forbidden line. The transition is statistically very unlikely, and it isn't detected in laboratories on Earth because the gas is too dense and the atoms collide too often. In space, however, hydrogen atoms collide only rarely, and hydrogen atoms can go undisturbed for millions of years. That allows them to produce the 21-cm radiation, and astronomers can use that radiation to map the location of the cold, low-density gas in our galaxy (■ Figure 10-7). Also, radio waves have



■ **Figure 10-7**

Most of the neutral hydrogen in the Milky Way Galaxy is in the plane of the disk-shaped galaxy—the bright band running from left to right. Notice how wispy and irregular the hydrogen is. (J. Dickey, UMn, F. Lockman, NRAO, SkyView) 21-cm radio observations reveal many clouds of neutral hydrogen orbiting the center of the galaxy, each with its individual Doppler shift. (Adapted from observations by Burton)

such long wavelengths that they are unaffected by the tiny dust grains in the interstellar medium, allowing astronomers to observe distant clouds that would be undetectable at shorter wavelengths.

Other atoms and molecules in the interstellar medium produce emission lines in the infrared and radio parts of the spectrum. A molecule can store energy by rotating at different speeds, by vibrating as if the atoms were linked by little springs, or by twisting back and forth. When an atom makes a transition from a high-energy state to a lower energy state, it can emit the excess energy as a photon. The CO molecule is an especially powerful emitter of radio energy, as is OH. You learned in Chapter 7 that the hydrogen Balmer lines lie in the visible and near-ultraviolet part of the spectrum, but other series of hydrogen lines lie in the infrared. Molecular hydrogen (H_2) and water also produce strong emission lines in the infrared. Silicate molecules contained in dust grains produce bands of strong infrared emission lines. Molecules called PAHs (polycyclic aromatic hydrocarbons) are organic molecules that float freely in space and are also found in dust grains. The strong infrared emission from PAHs

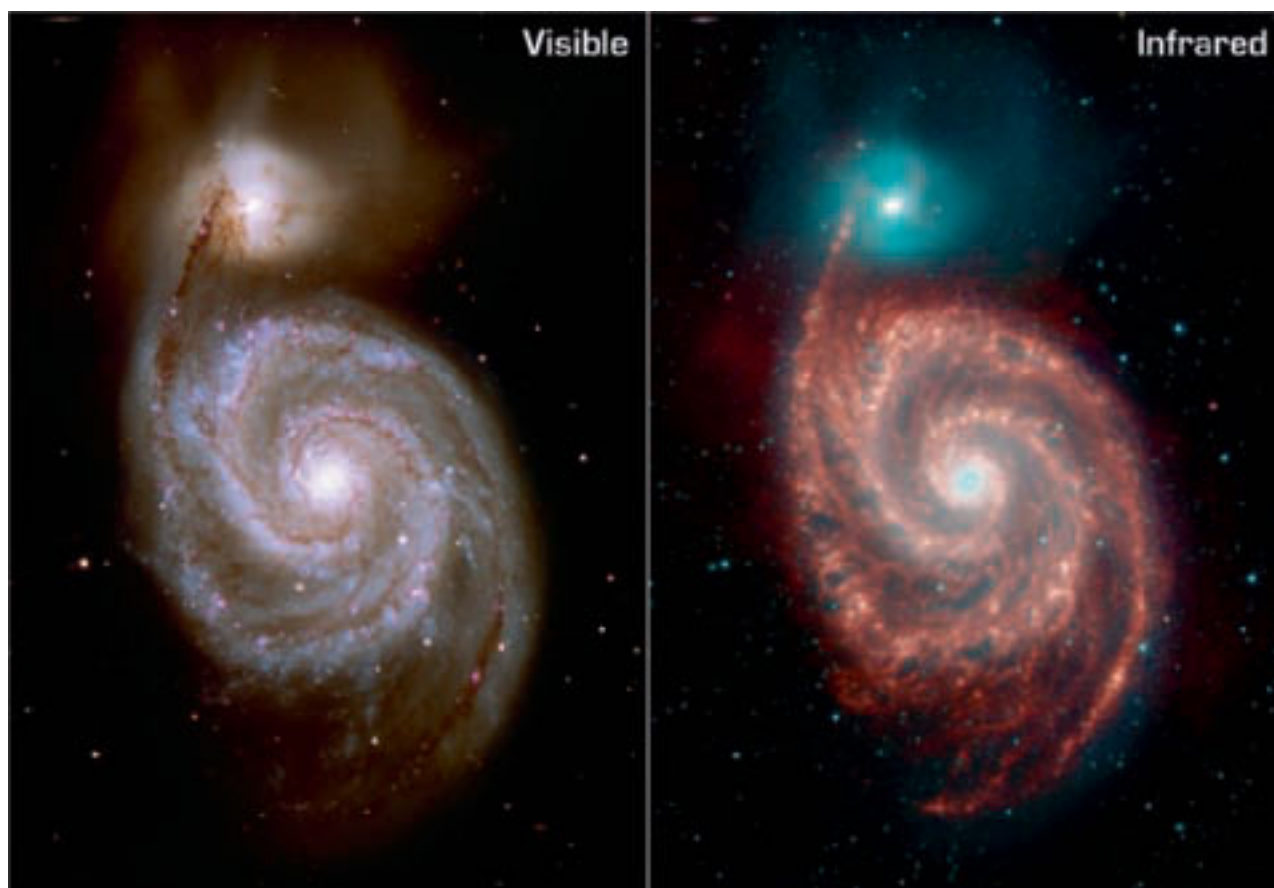
allows astronomers to study conditions in the interstellar medium throughout our galaxy and even in other nearby galaxies (■ Figure 10-8).

Other emission lines lie in the ultraviolet and X-ray part of the spectrum. In general, high-energy photons are produced by high-energy events, so X-ray observations tell you about very hot, excited gas such as matter expelled by the supernova explosions of stars. Infrared and radio emission lines tell you about colder, less excited gas such as frigid gas clouds quietly drifting through space (■ Figure 10-9). Observing at a wide range of wavelengths, astronomers have detected over 150 different molecules in the interstellar medium.

Infrared Radiation from Dust

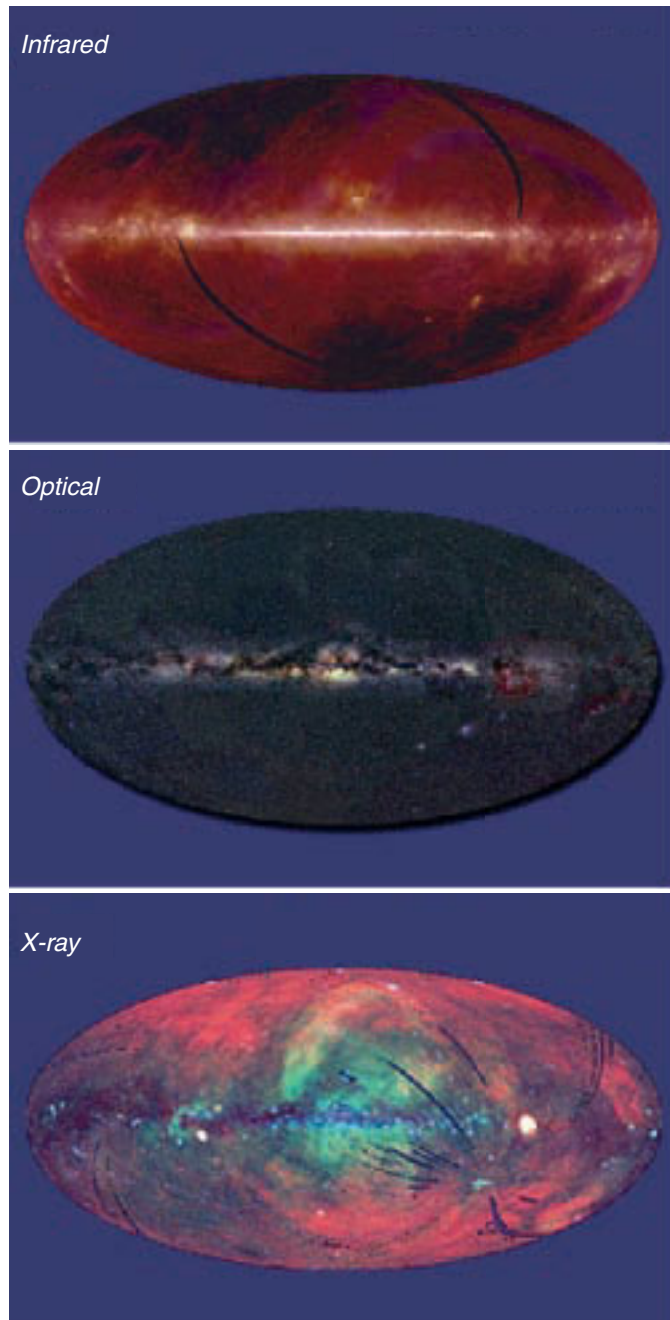
The dust in the interstellar medium makes up only about 1 percent of its total mass, and at a temperature of 100 K (-280°F) or less it is very cold. Nevertheless, it is easy to detect at infrared wavelengths.

You learned earlier that silicate molecules in dust grains produce strong spectral lines in the infrared, but the dust itself is also



■ **Figure 10-8**

At a distance of 23 million light-years, the galaxy M51, also known as the Whirlpool Galaxy, is similar to our Milky Way Galaxy. Infrared observations reveal it glowing from emission by complex molecules called PAHs (red). Many of these molecules are part of dust particles in the galaxy's interstellar medium. (KPNO, NASA)



■ **Figure 10-9**

These images of our galaxy include the entire sky spread into an oval. The infrared image shows the location of clouds of cold interstellar gas and dust made visible by blackbody radiation from dust grains. In the visual-wavelength image, dense, dusty clouds are silhouetted against distant stars. The X-ray image shows the location of very hot gas produced in most cases by the supernova explosions of dying stars. (NASA)

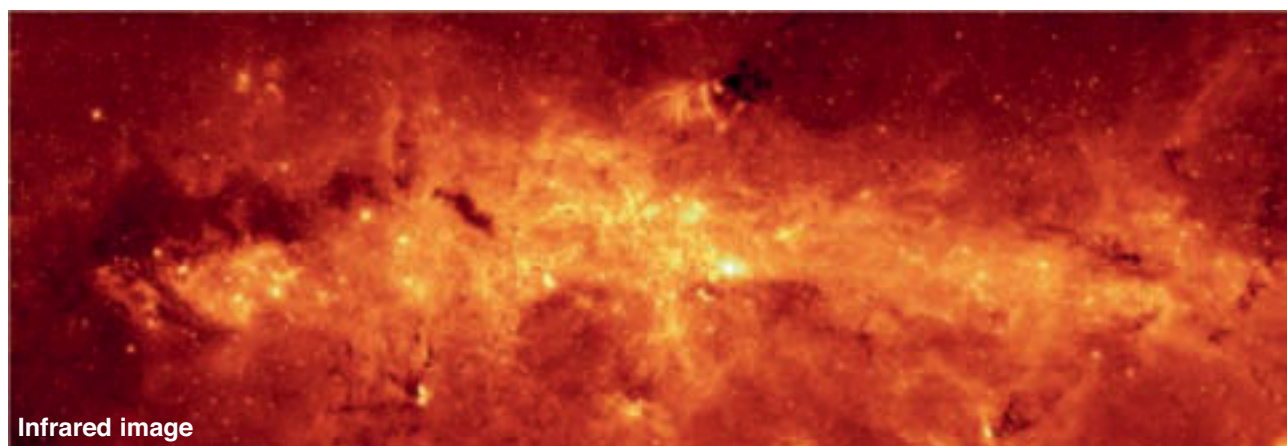
a powerful source of blackbody radiation. Although the dust can be very cold, 10 to 100 K, it is not at absolute zero, so it must radiate blackbody radiation, and at those temperatures, that radiation is emitted in the infrared.

You might wonder how such cold dust can be a powerful source of infrared radiation, but you must remember that the luminosity of an object depends on both its temperature and its surface area. To illustrate, imagine that you pack a solar mass of interstellar dust into a ball. It would be roughly the size of the sun. If you left that dust floating free in space, it would amount to more than a billion trillion trillion trillion (10^{45}) dust specks, each 0.001 mm in diameter or smaller. All that dust would have a surface area more than 10^{15} times larger than the sun's, and that means that even though it is very cold, the dust could radiate a huge amount of infrared radiation.

Infrared telescopes can map the interstellar medium by mapping the energy emitted by dust. Where the gas and dust are denser or where stars warm the dust, it is more luminous. ■ Figure 10-10 shows part of our Milky Way Galaxy aglow with radiation from dust at an infrared wavelength of 8 microns (8000 nm).

■ **Figure 10-10**

The Spitzer Space Telescope imaged the center of the Milky Way Galaxy at a wavelength of 8 microns (8000 nm) to reveal the distribution of the dusty interstellar medium. The brightest regions are clouds heated by young, massive stars. Individual stars can be seen as bright spots. (NASA/JPL-Caltech/S. Stolovy, Spitzer Science Center/Caltech)



Infrared image

Separating Facts from Hypotheses

When scientists disagree, what do they debate? The fundamental work of science is testing theories by comparing them with facts. The facts are evidence of how nature works, and they represent reality. Hypotheses are attempts to explain how nature works. Scientists are very careful to distinguish between the two.

Scientific facts are those observations or experimental results of which scientists are confident. Ornithologists might note that fewer mountain thrushes are returning each spring to a certain mountain valley. Counting bird populations reliably is difficult and requires special techniques, but if the scientists made the observations correctly, they can be confident of their result and treat it as a fact.

To explain the declining population of thrushes, the scientists might consider a number of hypotheses, such as global warming or chemical pollution in the food chain. The ornithologists are free to combine or adjust

their hypotheses to better explain the bird migration, but they are not free to adjust their facts. Scientific facts are the hard pebbles of reality that can't be changed.

New facts can aggravate debates that are already politically charged. The declining number of mountain thrushes, for example, could be unwelcome news because addressing the root problem might cost taxpayer dollars or hurt local business interests. Nonscientists sometimes debate an issue by trying to adjust or even deny the facts, but scientists are not free to ignore a fact because it is unpopular or inconvenient. Scientists debate an issue by arguing about which hypotheses best apply or how a hypothesis could be adjusted to fit the observed facts, but, once established, the facts themselves are not in question.

Whether scientists are measuring the density of an emission nebula or the size of a bird population, the final data become the



In science, evidence is made up of facts, which could range from precise numerical measurements to the observation of the shape of a flower.
(M. Seeds)

reality against which hypotheses are tested. When Galileo said we should “read the book of nature,” he meant we should consult reality as the final check on our understanding.

SCIENTIFIC ARGUMENT

What evidence can you cite that there is an interstellar medium? Everything in science is based on evidence, so your argument should discuss observations. First, there is the simple fact that certain parts of the interstellar medium are visible—the nebulae. Detailed analysis of emission and absorption lines show that all of interstellar space is filled by cold, thin gas. Extinction, reddening, and infrared observations show that some of the material is in the form of tiny dust specks.

Perhaps this is enough evidence to convince someone that the spaces between the stars are not empty, but there is more. Expand your argument. **What do infrared observations reveal about the interstellar gas?**

10-2 Components of the Interstellar Medium

YOU HAVE SEEN how astronomers can observe the interstellar medium at many different wavelengths, and those observations are the evidence against which they can test their theories (**How Do We Know? 10-1**). The observations clearly show that the interstellar medium is not uniform but is made up of different components.

Cool Clouds

The nebulae you see near hot, luminous stars are only small parts of the interstellar medium. Like the parts of a fog bank near streetlights, you see them easily because they are illuminated.

Most of the interstellar medium is invisible to human eyes and announces its presence strongly only at radio, infrared, ultraviolet, or X-ray wavelengths.

The multiple interstellar absorption lines seen in stellar spectra alerted you that some of the interstellar medium consists of clouds, and observations at infrared and radio wavelengths dramatically reveal clouds of cool gas and dust with densities of about 100 atoms per cubic centimeter. Because these clouds are not ionized, they are called **HI clouds**. They are 50 to 150 pc in diameter and have masses of a few solar masses. The gas temperature is only about 100 K. While it is easy to think of these clouds as more or less spherical blobs of gas, observations show that they are usually twisted, flattened, and tangled into chaotic shapes, as you can see in Figure 10-10—further evidence that the interstellar medium is not static and motionless.

The Intercloud Medium

The space between the cool HI clouds is filled by a hot **intercloud medium** with a temperature of a few thousand K and a density of only about 0.1 atom/cm³. The gas is partially ionized by the ultraviolet photons in starlight; but, although it is hot, it has such a low density it does not emit noticeable visible light.

In regions where the interstellar medium is in equilibrium (in other words, where the HI clouds are not expanding or contracting), the pressure in the cool clouds and the hot intercloud medium is about the same. The pressure in a gas depends on its density and its temperature (**Focus on Fundamentals 5**). The HI clouds are cool but dense, and the gas of the intercloud

Pressure

One of the most fundamental parameters in science is **pressure**, a measure of force per unit area. If you are going to understand astronomy, you must be sure you understand pressure. Doctors measure blood pressure, and astronomers measure gas pressure, but they are really measuring the same fundamental parameter.

Pressure is expressed in the units of force per unit area. If you inflate the tires on a car, in the United States you use the unit pounds per square inch. A typical pressure might be 34 lb/in². It is important to note that this is not the total force pushing out on the inside of the tire but only the force exerted on a single square inch. When you stand, your weight exerts a force on the floor, and the pressure under your shoes is your weight divided by the surface area of your shoes' soles. A typical pressure might be only 4 lb/in². If you step on someone's toe, that is the pressure you exert. Of course, if you were wearing ice skates, your weight would be spread over a much smaller area, the area of the bottom of the blade, and

you might exert a pressure of 150 lb/in² or more. That's why skaters must be careful not to step on someone's toe. The pressure would be dangerously high.

Astronomers are most commonly interested in the behavior of matter when it is a gas, and pressure in a gas arises when atoms or molecules collide. Consider, for example, how the gas molecules colliding with the inside of a balloon exert an outward force on the rubber and keep the balloon inflated. If the gas is hot, the atoms or molecules move rapidly, and the resulting pressure is higher than for a cooler gas. If the gas is dense, there will be many gas particles colliding with the inside of the balloon, and the pressure will be higher than for a lower-density gas. In this way, pressure depends on both the temperature and the density of the gas.

Pressure and density are related, but they are not at all the same thing. Density is a measure of the amount of matter in a given volume, and pressure is a measure of the force that matter exerts on its surroundings.



Pressure pushes outward on the inside of a balloon.

A very-low-density gas and a very-high-density gas might have the same pressure if they had different temperatures.

In daily life, you think of pressure when you inflate an automobile tire, but pressure is common in nearly all of the sciences. Astronomers must consider pressure in thinking about the gas inside stars and the thin gas between the stars.

MASS | ENERGY | TEMPERATURE AND HEAT | DENSITY | PRESSURE

medium is hot but low in density. That means the two regions can have similar pressures even though their temperatures are quite different and allows the HI clouds and the intercloud medium to be stable and to coexist.

By now you are probably wondering how the intercloud medium could be ionized when it is not close to hot stars. To understand why it is ionized, imagine that you are an atom floating in the intercloud medium. Ultraviolet photons from distant stars are not common, but they do whiz past you now and then. Soon you absorb one of these photons and become ionized by losing an electron. In a denser gas, you would quickly find another electron, capture it, and become a neutral atom again, but the interstellar medium has such a low density that the gas particles are spread far apart. You must wait a very long time before an electron comes close enough for you to capture. That is why the gas of the intercloud medium is ionized; the atoms spend almost all their time waiting for an electron to wander past.

Molecular Clouds

Radio and infrared observations of the interstellar medium reveal some clouds of gas and dust with densities ranging from hundreds to a thousand particles (atoms and molecules) per cubic

centimeter. These clouds are called **molecular clouds** because they are dense enough to form molecules deep inside where the dust protects the molecules from ultraviolet photons, which would break up the fragile molecules.

Molecular clouds are very cold, only a few degrees above absolute zero, and much of the gas is in the form of molecules. Molecular hydrogen (H₂) is the main gas, but that molecule is difficult to detect, so astronomers typically study the clouds by studying radio emission from other molecules such as carbon monoxide (CO). Although CO is 10,000 times less common in the clouds than is H₂, the CO molecules are a strong source of radio emission at a wavelength of 2.6 mm in the microwave part of the radio spectrum. Over 150 other molecules including OH, N₂O (nitrous oxide, which some humans inhale), and ethyl alcohol (which some humans drink) have been detected in molecular clouds, but the overall composition of the clouds is the same as the interstellar medium in general; they are about 70 percent hydrogen, 28 percent helium, and 2 percent heavier atoms. The difference is that they are dense enough and cold enough for the atoms to link together and form molecules.

The CO molecules and the dust in the cloud tend to keep it cold. CO and dust are very good at radiating infrared radiation,

and the cloud is transparent to infrared wavelengths. So the infrared photons zip out of the clouds carrying away energy, and that keeps the temperature low.

Molecular clouds contain up to a few hundred solar masses, but **giant molecular clouds** contain up to a million solar masses. They can be 100 pc (300 ly) in diameter and in their densest cores can contain 100,000 particles per cubic centimeter. The giant molecular clouds tend to form from gas that has settled toward the plane of our galaxy, and you can see a number of them as dark nebulae that obscure stars and form the Great Rift along the center of the Milky Way (p. 195). Thousands of giant molecular clouds exist in our galaxy.

Giant molecular clouds are the nests of star birth. Deep inside these great clouds, gravity can pull the matter inward and create new stars (■ Figure 10-11). That is a story you will follow in detail in the next chapter. For now, you can learn more about the interstellar medium by examining its hottest component.

Coronal Gas

The interstellar medium seems very cold, so you would hardly expect to find it emitting X-rays because such high-energy photons

are commonly produced by high temperatures. Nevertheless, X-ray telescopes above Earth's atmosphere have detected X-rays from parts of the interstellar medium. This gas has been called the **coronal gas** because it has temperatures of 10^6 K or higher, similar to the sun's corona. Of course, the coronal gas in the interstellar medium is not related in any way to the actual corona of the sun.

You might expect the coronal gas to have a very high pressure because it is so hot, but actually it has a very low density. It contains only 0.003 to 0.0004 particle/cm³. That is, you would have to search through a few hundred to a few thousand cubic centimeters of coronal gas to find a single particle—an ionized atom or an electron. Because of its very low density, the gas pressure in the coronal gas can be roughly the same as in the HI clouds, and the intercloud medium can stay in equilibrium (not expand or contract).

Coronal gas is evidently produced when a massive star dies violently in a supernova explosion. Although they are rare, such explosions blast large amounts of very hot gas outward in expanding bubbles. Gas flowing away from very hot, young stars can also produce coronal gas (■ Figure 10-12). In some cases, neighboring bubbles of coronal gas may expand into each other and merge to form larger volumes called superbubbles. Such regions are impor-



■ **Figure 10-11**

A giant molecular cloud collapsed and began forming stars a few million years ago, including three star clusters visible in this image. Intense radiation and outflowing gas from the hottest, most luminous of these stars is eating into the dark molecular cloud and exciting some of its gases to glow. The nebula is located 210,000 ly from Earth in a nearby galaxy. (NASA, ESA, and A. Nota, STScI/ESA)



■ **Figure 10-12**

Intense star formation within this cloud is blowing it apart. On the right side of this image, roughly 200 hot, young, massive stars are inflating bubbles of coronal gas, shown as blue in the X-ray image. On the left side of the diagram, the expanding clouds of coronal gas come from hot stars plus a number of past supernova explosions. (X-ray: NASA/CXC/CfA/R. Tuellmann et al.; Optical: NASA/AURA/STScI)

tant because the expanding gas may compress nearby clouds and trigger star formation. Probably about 20 percent of the space between the stars is filled with bubbles of coronal gas.

Far-ultraviolet and X-ray observations reveal that the sun is located just inside a region of coronal gas roughly 100 pc in diameter filled with hot, ionized hydrogen. This **local bubble** (or **local void**) of gas in which the sun is located was inflated when a supernova exploded near the sun within the last few million years and may be linked to other hot, transparent regions.

Observations at many wavelengths show that the interstellar medium is complex with four different components (■ Table 10-1). The exact proportions are not well known, but cool clouds probably make up very roughly 20 percent of the mass and the intercloud medium about 50 percent. The molecular clouds are dense and make up about 20 percent of the mass, and the low-density coronal gas, although it occupies a large volume, amounts to only about 10 percent of the mass in the interstellar medium. In fact the four-component picture is a simplified model of the real situation, but it is adequate to portray the general properties of the interstellar medium.

■ **Table 10-1** | **Four Components of the Interstellar Medium**

Component	Temperature (K)	Density (atoms/cm ³)	Gas State
Molecular clouds	20–50	10 ³ –10 ⁵	Molecules
HI clouds	50–150	1–1000	Neutral hydrogen; other atoms
Intercloud medium	10 ³ –10 ⁴	0.01	Partially ionized
Coronal gas	10 ⁵ –10 ⁶	10 ⁻⁴ –10 ⁻³	Highly ionized

SCIENTIFIC ARGUMENT

If hydrogen is the most common molecule, why do astronomers depend on the CO molecule to map molecular clouds?

This scientific argument links a bit of atomic physics with the chain of inference that leads from what can be observed to what astronomers need to know. Although hydrogen is the most common atom in the universe and molecular hydrogen the most common molecule, molecules of hydrogen do not radiate easily in the radio part of the spectrum. But the much less common CO (carbon monoxide) molecule is a very efficient radiator of radio energy, so radio astronomers use it as a tracer of molecular clouds. Wherever radio telescopes reveal a great cloud of CO, you can be confident that most of the gas is molecular hydrogen.

You can also be confident that the molecular clouds contain dust, because it is the dust that protects the molecules in the cloud from the ultraviolet radiation that would otherwise break the molecules into atoms.

At the temperatures found in the interstellar medium, dust doesn't radiate very much longer-wavelength radio energy, but you can study it in the infrared. Although the dust in a molecular cloud is very cold and makes up a small percentage of the total mass, it is a very good radiator of infrared radiation. Create a new argument using the physics of infrared emission from dust to answer a different question: **How can a small mass of cold dust radiate vast amounts of infrared radiation?**

10-3 The Gas-Star-Gas Cycle

THE INTERSTELLAR MEDIUM IS COMPLEX and, in some cases, quite beautiful, but it would be just a curiosity if it were not intimately related to stars. Stars are born from the interstellar medium, and aging stars return gas and dust back into the interstellar medium. As you learn about that cycle, you are beginning to learn about the life story of the stars that will be portrayed in the next few chapters.

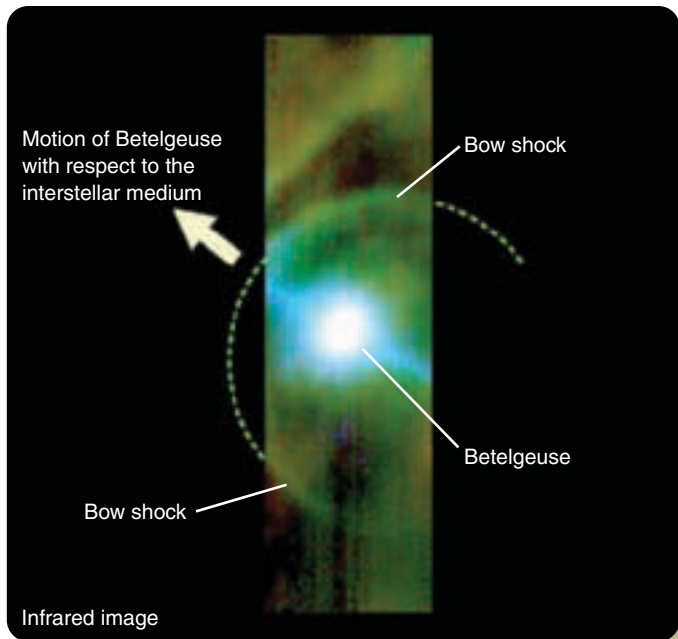
Gas and Dust from Aging Stars

Astronomers have clear evidence that much of the hydrogen and helium in the interstellar medium is gas left over from the formation of our galaxy over 10 billion years ago, so that gas has never been inside stars. But some of the gas and dust that lie between the stars has been produced in stars and expelled as the stars aged.

The sun exhales gas and dust in the solar wind, but that is a gentle breeze compared to the wind blown out of aging stars. The atmospheres of those stars are so cool that some atoms can condense to form specks of dust, including carbon and silicon. The pressure of the starlight pushes those dust specks out of the star along with a powerful flow of hydrogen, helium, and other gases (■ Figure 10-13). The sun, for example, will blow away almost half of its mass in a relatively short episode before it reaches its final fate in about five billion years. Thus, part of the gas and dust in the interstellar medium has been exhaled by stars.

In later chapters, you will learn that some stars die in violent supernova explosions that blast matter outward in expanding clouds of hot gas. Much of the coronal gas in the interstellar medium is produced by supernova explosions. As those gases cool, dust condenses like soot from a candle flame, so supernovae add large amounts of dust to the interstellar medium. As you will learn in a later chapter, other types of stars end their lives less violently but also contribute substantial amounts of material to the interstellar medium.

Supernova explosions and the blasts of light and gas blowing away from the hottest stars keep the interstellar medium stirred with **shock waves**, the astronomical equivalent of sonic booms. As those shock waves sweep through the interstellar medium, they compress gas and form clouds dense enough for molecules to begin forming. Many of the molecular clouds in the galaxy have been twisted, distorted, and compressed by shock waves.



■ **Figure 10-13**

The red giant star Betelgeuse is blowing away a powerful wind of gas and dust at 17 km/s. Where that wind collides with the interstellar medium, it forms a bow shock much like the bow wave in front of a speed boat. The bow shock is not centered on the star because it is speeding through the interstellar medium as shown by the arrow in the figure. (Ueta et al, PASJ, 2008)

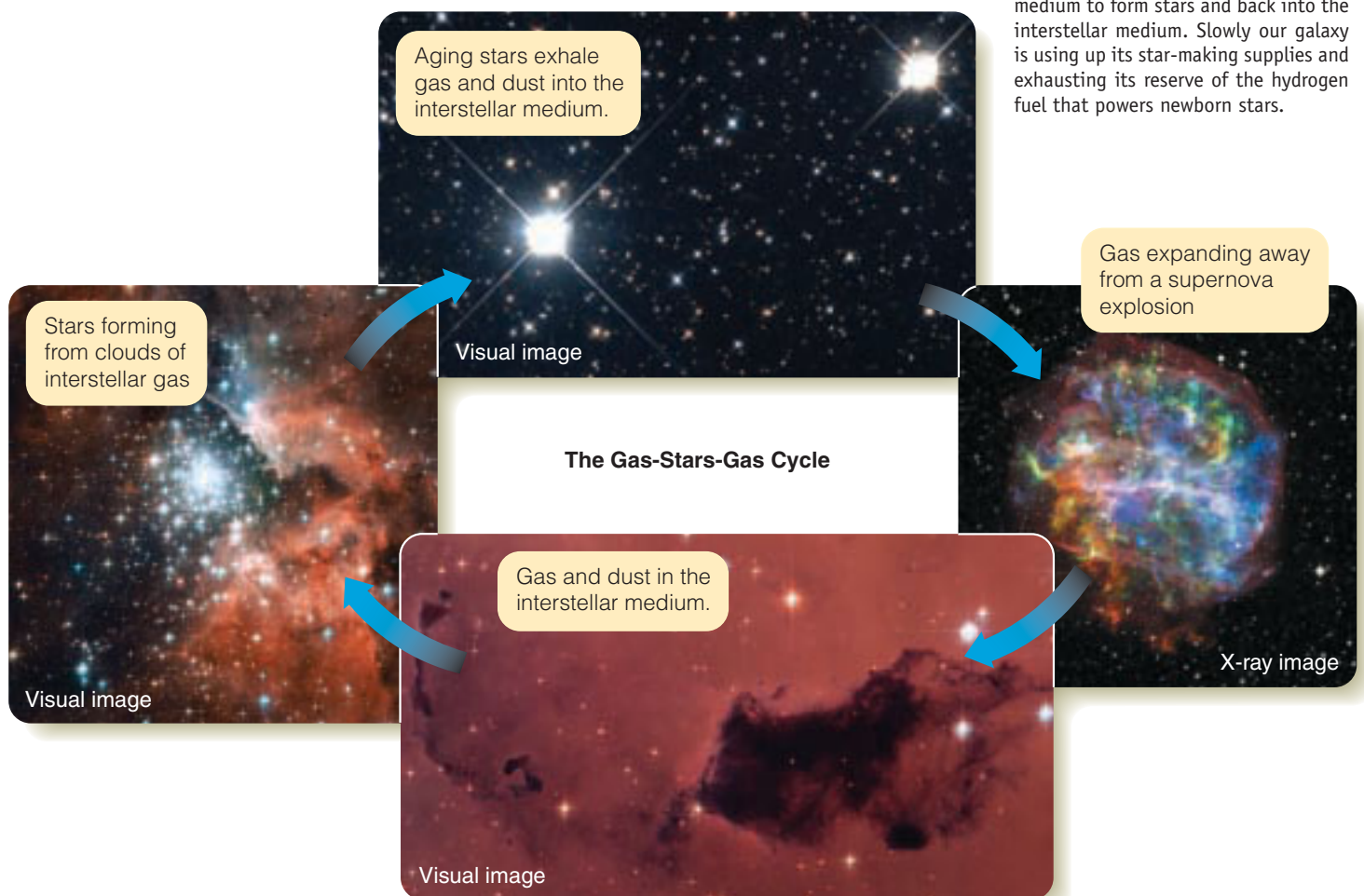
A Preview of Star Formation

Molecular clouds form as the interstellar medium is compressed, and gravity and turbulence tend to concentrate these clouds to form giant molecular clouds. Such clouds are located along the spiral arms of our galaxy.

Because these clouds of gas are so cool, gravity can squeeze them to higher densities, especially if they are compressed further by a passing shock wave. The densest regions of molecular clouds can become gravitationally unstable, meaning the gravity pulling the gas together is stronger than the pressure and turbulence in the gas. As the gas falls together, the dense cores break into fragments and form clusters of stars. A single giant molecular cloud can sometimes form a number of clusters of stars.

■ **Figure 10-14**

Matter cycles from the interstellar medium to form stars and back into the interstellar medium. Slowly our galaxy is using up its star-making supplies and exhausting its reserve of the hydrogen fuel that powers newborn stars.



The most massive stars to form are the hottest and exhale gas most violently. Also, as you will learn in a few chapters, the most massive stars live very short lives—only a few million years—and die in violent supernova explosions blasting more gas back into the interstellar medium.

A giant molecular cloud can make lots of stars, but as supernovae begin expelling coronal gas, the molecular cloud can be ripped apart and mixed back into the general interstellar medium, and that closes the circle on the gas-stars-gas cycle (■ Figure 10-14).

As matter in our galaxy passes through this cycle, some of the mass gets incorporated into low-mass stars that live very long

times or gets trapped in remnants of stars like white dwarfs, neutron stars, and black holes that you will learn about in later chapters. Consequently, the matter in those remnants is removed from the cycle. Also, with each cycle some of the hydrogen gets fused into helium and heavier atoms like carbon, nitrogen, and oxygen. Thus, as the eons pass, our galaxy is gradually using up its star-making mass and hydrogen fuel as it forms stars. Also, with each generation of stars, the interstellar medium becomes richer in those heavier atoms, and the chemical composition of the interstellar medium slowly changes. In a later chapter, that will give you a critical clue to understanding the life story of our galaxy.

What Are We? Drifters

City dwellers see only the brightest stars scattered across the sky, but even those who live far from city lights see almost nothing between the stars. It is easy to imagine that space is empty. Only a few hazy nebulae such as that in Orion's sword hint at the hidden richness of space.

We live in a universe filled with beauty beyond our senses. Special telescopes and cameras can capture photographs of glowing gas containing brilliant stars and dark clouds of gas twisting through space. Clouds of neutral gas, cold dust, and hot bubbles of coronal gas are not visible to our eyes, but they are part of the complex beauty of the

interstellar medium. All around us, stars drift through an invisible ocean whose peaceful reaches are blasted here and there by storms of light and heat as the interstellar medium interacts with the stars.

Science enriches our lives by revealing the beauty we cannot sense directly.

Study and Review

Summary

- ▶ The **interstellar medium (ISM)** (p. 193), the gas and dust between the stars, is mostly concentrated near the plane of our Milky Way Galaxy and has an average density of about one atom per cubic centimeter.
- ▶ A **nebula** (p. 193) is a cloud of gas in space, and an **HII region** (p. 194) (also known as an **emission nebula** [p. 194]) is produced when ultraviolet radiation from hot stars ionizes nearby gas, making it glow like a giant neon sign. The red, blue, and violet Balmer lines blend together to produce the characteristic pink-red color of ionized hydrogen.
- ▶ A **reflection nebula** (p. 194) is produced by gas and dust illuminated by a star that is not hot enough to ionize the gas. Rather, the dust scatters the starlight to produce a reflection of the stellar absorption spectrum. Because shorter-wavelength photons scatter more easily than longer-wavelength photons, reflection nebulae look blue. The daytime sky looks blue for the same reason.
- ▶ A **dark nebula** (p. 195) is a cloud of gas and dust that is noticeable because it blocks the light of distant stars. The irregular shapes

of these dark nebulae reveal the turbulence in the interstellar medium.

- ▶ **Interstellar dust** (p. 196) makes up roughly 1 percent of the mass of the interstellar medium. The remaining 99 percent of the mass is gas.
- ▶ About 70 percent of the mass of the interstellar medium is hydrogen gas, and 28 percent is helium. About 2 percent is atoms heavier than helium. This is approximately the same composition as the sun and other stars.
- ▶ The gas in nebulae has a low density, and the atoms collide so rarely that an electron caught in a **metastable level** (p. 196) can remain there long enough to finally fall to a lower level and emit a photon. This produces so-called **forbidden lines** (p. 196) that are not seen in laboratory spectra on Earth where the atoms in the gas collide too often.
- ▶ **Interstellar extinction** (p. 196), or dimming, makes the distant stars look fainter than they should. **Interstellar reddening** (p. 196) makes distant stars appear too red because dust particles in the interstellar medium scatter blue light more easily than red light. The dependence of this extinction on wavelength shows that the scattering dust

particles are very small. The dust is made of carbon, silicates, iron, ice, and other common atoms and molecules.

- ▶ The interstellar gas is cold and has a very low density, and this makes **interstellar absorption lines (p. 197)** much narrower than the spectral lines produced in stars. Such lines are usually obvious in stellar spectra because they represent ions that cannot exist in the atmospheres of the stars. Interstellar lines stand out in the spectra of spectroscopic binaries because they do not shift their wavelengths as do lines produced by the orbiting stars. Multiple interstellar lines reveal that the light has passed through more than one interstellar cloud on its way to Earth.
- ▶ The low-density gas of the interstellar medium also produces emission lines at many wavelengths. The **21-cm radiation (p. 198)** is a forbidden line produced when the electrons in hydrogen atoms change the direction of their spin and emit radio wavelength photons. This radiation allows radio astronomers to map the distribution of neutral hydrogen gas in the interstellar medium.
- ▶ Radio, infrared, and X-ray telescopes have detected emission from over 150 different molecules in the interstellar medium.
- ▶ Interstellar dust, although it is very cold, emits blackbody radiation; and, because the dust in an interstellar cloud has a huge surface area, it can emit large amounts of long-wavelength infrared radiation.
- ▶ The interstellar medium is made up of four main components. **HI clouds (p. 202)** of neutral hydrogen are cold clouds containing a few solar masses in a region 10 to 150 pc in diameter. They are separated from each other by a hotter but lower-density gas called the **intercloud medium (p. 202)**, and the two generally have similar **pressures (p. 203)** and are in equilibrium.
- ▶ Large, dense clouds of gas and dust are called **molecular clouds (p. 203)** because they are so dense molecules can form inside them. Such clouds can be mapped by the radio photons emitted by CO and OH molecules. Hydrogen molecules (H_2) do not radiate at radio wavelengths. The largest of these are called **giant molecular clouds (p. 204)** and are the sites of star formation.
- ▶ Molecules can be broken up by short-wavelength photons, but the dust in molecular clouds scatters these photons and shields the molecules in the inner part of the cloud. Because the molecules are so good at radiating energy away, they keep the clouds very cold.
- ▶ X-ray observations have detected very hot **coronal gas (p. 204)**, the fourth component of the interstellar medium. It is produced by hot gas blown away from massive stars and gas expelled from supernova explosions. Far-ultraviolet observations show that the sun is located in a **local bubble (or local void) (p. 205)** of coronal gas that was apparently produced by a supernova explosion near the sun within the last few million years.
- ▶ The interstellar medium interacts with the stars through a gas-star-gas cycle. Hot stars and supernovae expel gas and dust into the interstellar medium, and cool stars contribute more gas and dust. The gas and dust collects into giant molecular clouds where new stars form singly or in clusters. Star formation ends in a molecular cloud when hot gas from newborn massive stars and supernovae form **shock waves (p. 205)** and blow the cloud apart.
- ▶ As matter in our galaxy passes through the gas-star-gas cycle, some is trapped in low-mass stars and black holes. Also, more and more hydrogen is converted into helium and heavier elements. In this way, our galaxy is gradually using up its star-making supplies.

Review Questions

1. What evidence visible to human eyes can you cite that the spaces between the stars are not totally empty?
2. What evidence can you cite that the interstellar medium contains both gas and dust?
3. How do the spectra of HII regions differ from the spectra of reflection nebulae? Why?
4. How is the blue color of a reflection nebula related to the blue color of the daytime sky?
5. Why do distant stars look redder than their spectral types suggest?
6. Why are interstellar lines so narrow? Why do some spectral lines forbidden in spectra on Earth appear in spectra of interstellar clouds and nebulae? What does that tell you?
7. Why can the 21-cm radio emission line of neutral hydrogen be observed in the interstellar medium but not easily in the laboratory?
8. How can the HI clouds and the intercloud medium have similar pressures when their temperatures are so different?
9. Why can molecular clouds form molecules in their interiors while HI clouds cannot?
10. What produces the coronal gas?
11. How does the interstellar medium interact with stars?
12. **How Do We Know?** Why are scientists free to adjust their hypotheses but not their facts?

Discussion Questions

1. When you see distant streetlights through smog, they look dimmer and redder than they do normally. But when you see the same streetlights through fog or falling snow, they look dimmer but not redder. Use your knowledge of the interstellar medium to discuss the relative sizes of the particles in smog, fog, and snowstorms compared to the wavelength of light.
2. If you could see a few stars through a dark nebula, how would you expect their spectra and colors to differ from similar stars just in front of the dark nebula?

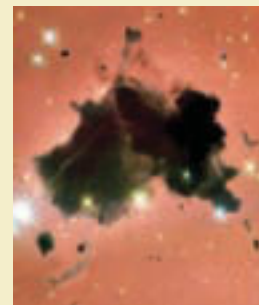
Problems

1. A small nebula has a diameter of 20 arc seconds and a distance of 1000 pc from Earth. What is the diameter of the nebula in parsecs? In meters? (*Hint:* Use the small-angle formula, Chapter 3.)
2. The dust in a molecular cloud has a temperature of about 50 K. At what wavelength does it emit the maximum energy? (*Hint:* Consider blackbody radiation, Chapter 7.)
3. Extinction dims starlight by about 1 magnitude per 1000 pc. What fraction of photons survives a trip of 1000 pc? (*Hint:* Consider the definition of the magnitude scale in Chapter 2.)
4. If the total extinction through a dark nebula is 10 magnitudes, what fraction of photons makes it through the cloud? (*Hint:* See Problem 3.)
5. The density of air in a child's balloon 20 cm in diameter is roughly the same as the density of air at sea level, 10^{19} particles/cm³. To how large a diameter would you have to expand the balloon to make the gas inside the same density as the interstellar medium, about 1 particle/cm³? (*Hint:* The volume of a sphere is $\frac{4}{3}\pi R^3$.)

6. If a giant molecular cloud has a diameter of 30 pc and drifts relative to neighboring clouds at 20 km/s, how long will it take to travel its own diameter?
7. An HI cloud is 4 pc in diameter and has a density of 100 hydrogen atoms/cm³. What is its total mass in kilograms? (*Hint:* The volume of a sphere is $\frac{4}{3}\pi R^3$, and the mass of a hydrogen atom is 1.67×10^{-27} kg.)
8. Find the mass in kilograms of a giant molecular cloud that is 30 pc in diameter and has a density of 300 hydrogen molecules/cm³. (*Hint:* See Problem 7.)
9. At what wavelength does the coronal gas radiate most strongly? (*Hint:* Consider blackbody radiation, Chapter 7.)

Learning to Look

1. At visual wavelengths, the bright-blue star at the center of the images in Figure 10-4 is surrounded by a blue nebula. What can you conclude about the temperature of this star?
2. The image at right shows two nebulae, one pink in the background and one black in the foreground. What kind of nebulae are these?



NASA and the Hubble Heritage Team,
STScI/AURA

11

The Formation and Structure of Stars



Infrared image

Guidepost

The last chapter introduced you to the gas and dust between the stars that are raw material for new stars. Here you will begin putting together observations and theories to learn how nature makes stars from the interstellar medium and to understand the internal structure of stars. That will answer four essential questions:

— **How do stars form?**

— **What is the evidence that theories of star formation are correct?**

— **How do stars maintain their stability?**

— **How do stars make energy?**

As you finish this chapter you will have gained a view of the exciting and energetic infancy of stars. In the next chapter, you will follow stars into their stable, slowly evolving adult life stage, called the main sequence.

This infrared image of the Great Nebula in Orion shows cool protostars (depicted as orange) deeply embedded in the gas and dust of a giant molecular cloud, as well as newborn stars that are just blowing their dust cocoons away, plus abundant raw material for new stars. (Mark McCaughrean [AI Potsdam] et al., ISAAC, VLT ANTU, ESO)

Jim he allowed [the stars] was made, but I allowed they happened. Jim said the moon could'a laid them; well, that looked kind of reasonable, so I didn't say nothing against it, because I've seen a frog lay most as many, so of course it could be done.

— MARK TWAIN, *THE ADVENTURES OF HUCKLEBERRY FINN*

THE STARS ARE NOT ETERNAL. When you look at the sky, you see hundreds of points of light, and, amazingly enough, each one, like the sun, is a tremendous nuclear fusion reactor held together by its own gravity. The stars you see tonight are the same stars your parents, grandparents, and great-grandparents saw. Stars don't change perceptibly in a person's lifetime, even during all of human history, but they do not last forever. Stars are “born,” and stars “die.” This chapter begins that story.

How can you know what the life cycles and internal processes of stars are, given that you won't live long enough to see them evolve, and you can't see inside them? The answer lies in the methods of science. By constructing theories that describe how nature works and then testing those theories against evidence from observations, you can unravel some of nature's greatest secrets. In this chapter, you will see how gravity creates stars from the thin material of interstellar space. You will then learn more about how the flow of energy from the insides of stars outward toward their surfaces balances gravity and makes the stars stable, and how nuclear reactions in the cores of stars ultimately supply that energy flow. To understand this story, you will plunge from the cold gas of the interstellar medium into the hot centers of the stars themselves.

11-1 Making Stars from the Interstellar Medium

ASTRONOMERS FIND HUNDREDS of places in the sky where clouds of gas glow brightly because they are illuminated by the hottest, most massive and luminous stars, of spectral types O and B. As you will learn in detail in Chapter 12, those kinds of stars pour out such floods of energy that they can last only a few million years, so you must be seeing them pretty near where they were born. O and B stars are therefore signposts pointing to star-forming regions, which are always among the densest parts of the interstellar medium (■ Figure 11-1).

Star Birth in Giant Molecular Clouds

As you saw in the previous chapter, spectra of the interstellar medium (ISM) show that its chemical composition is basically the same as stars. By observing at far-infrared and radio wavelengths, to



■ **Figure 11-1**

Nebula NGC 1333 is filled with newborn stars caught in the act of forming in this infrared image. (NASA/JPL-Caltech/R. A. Gutermuth, Harvard-Smithsonian CfA)

which interstellar dust is basically transparent, astronomers can peer inside even dense molecular clouds and find evidence that stars are forming there. In fact, the giant molecular clouds discussed in the preceding chapter are each massive enough to make thousands of new stars. But how do those large low-density clouds of cold gas and dust become comparatively small, high-density, hot stars?

Giant molecular clouds have typical diameters of 50 pc and typical masses exceeding 10^5 solar masses, vastly larger than a single star. The gas in a giant molecular cloud is about 10^{20} times less dense than a star and has temperatures of only a few degrees Kelvin. Those clouds can form into stars only if small regions of the cloud can be compressed somehow to high density and high temperature. But at least four factors resist the compression of an interstellar gas cloud, and those factors must be overcome by gravity before star formation can begin.

First, thermal energy in the gas appears as motion of the atoms and molecules. Even at the very low temperature of 10 K, the average hydrogen molecule moves at about 0.33 km/s (about 740 mph). This thermal motion would make the cloud come apart if gravity were too weak to hold it together.

Second, the interstellar medium is filled with a magnetic field. The ISM field is only about 0.0001 times as strong as Earth's magnetic field, but that is enough to act as an internal spring and prevent the gas from contracting. Neutral atoms and molecules are unaffected by a magnetic field, but ions, having an electric charge, cannot move freely through a magnetic field. Although the gas in a molecular cloud is mostly neutral, some ions are included, and that means a magnetic field can exert a force on the gas as a whole. Gravity must overcome the interstellar magnetic

field to make the gas contract. Under some conditions, the ionized gas in giant molecular clouds can gradually recombine with free electrons. The resulting less-ionized gas is freer to “slip past” the magnetic field and contract. This process has been observed inside isolated molecular clouds.

Third, everything in the universe rotates. As a gas cloud begins to contract, it spins more and more rapidly as it conserves angular momentum, just as ice-skaters spin faster as they pull in their arms (see Figure 5-7). This rotation can become so rapid that it resists further contraction of the cloud.

Fourth, turbulence in the interstellar medium can prevent a cloud from contracting. In the previous chapter, you learned that nebulae are often twisted and distorted by strong currents. This turbulence can help prevent a molecular cloud from contracting.

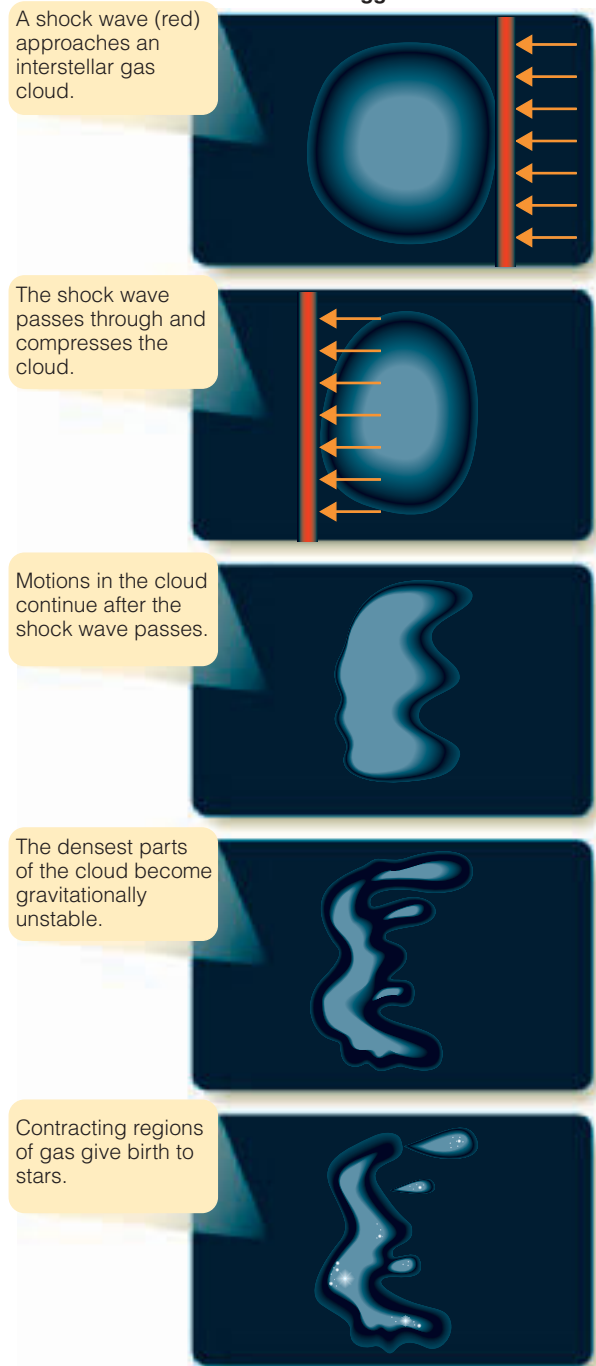
Given these four resisting factors, it may seem surprising that any giant molecular clouds can contract at all, but radio and infrared observations show that at least some giant molecular clouds develop concentrated regions called dense cores that are roughly 0.1 pc in size and contain about 1 solar mass. A single giant molecular cloud may contain many of these dense cores, each perhaps destined to become a star.

Both theory and observation suggest that giant molecular clouds can be triggered to form stars by a passing shock wave, sometimes just called a **shock**, the astronomical equivalent of a sonic boom (■ Figure 11-2). During such a triggering event, some regions of the large cloud can be compressed to such high densities that the resisting factors can no longer oppose gravity, and star formation begins.

Shock waves that can trigger star formation are common in the interstellar medium. For example, gas flows of several sorts produce shocks when they push into colder, denser interstellar matter. Supernova explosions (Chapter 13) create powerful shock waves that rush through the interstellar medium (■ Figure 11-3a). Also, the ignition of very hot stars ionizes nearby gas and causes it to flow rapidly away (Figure 11-3b). New stars of all types seem to emit strong winds and jets while they are forming. Each of those kinds of flows can also produce shocks. A second type of star formation trigger is the collision of molecular clouds. Because the clouds are large, they are likely to run into each other occasionally, and because they contain magnetic fields they cannot easily pass through each other. A collision between such clouds can compress parts of the clouds and cause star formation. A third type of trigger is the spiral pattern of our Milky Way Galaxy (see Figure 1-11). Theory and evidence both indicate that spiral arms are shock waves that travel around the disk of the galaxy like the moving hands of a clock (Chapter 15). As a cloud passes through a spiral arm, the cloud can be compressed, and star formation may begin. Astronomers have found regions of star formation in which each of these trigger processes can be identified.

A single giant molecular cloud containing a million solar masses does not contract to form a single humongous star.

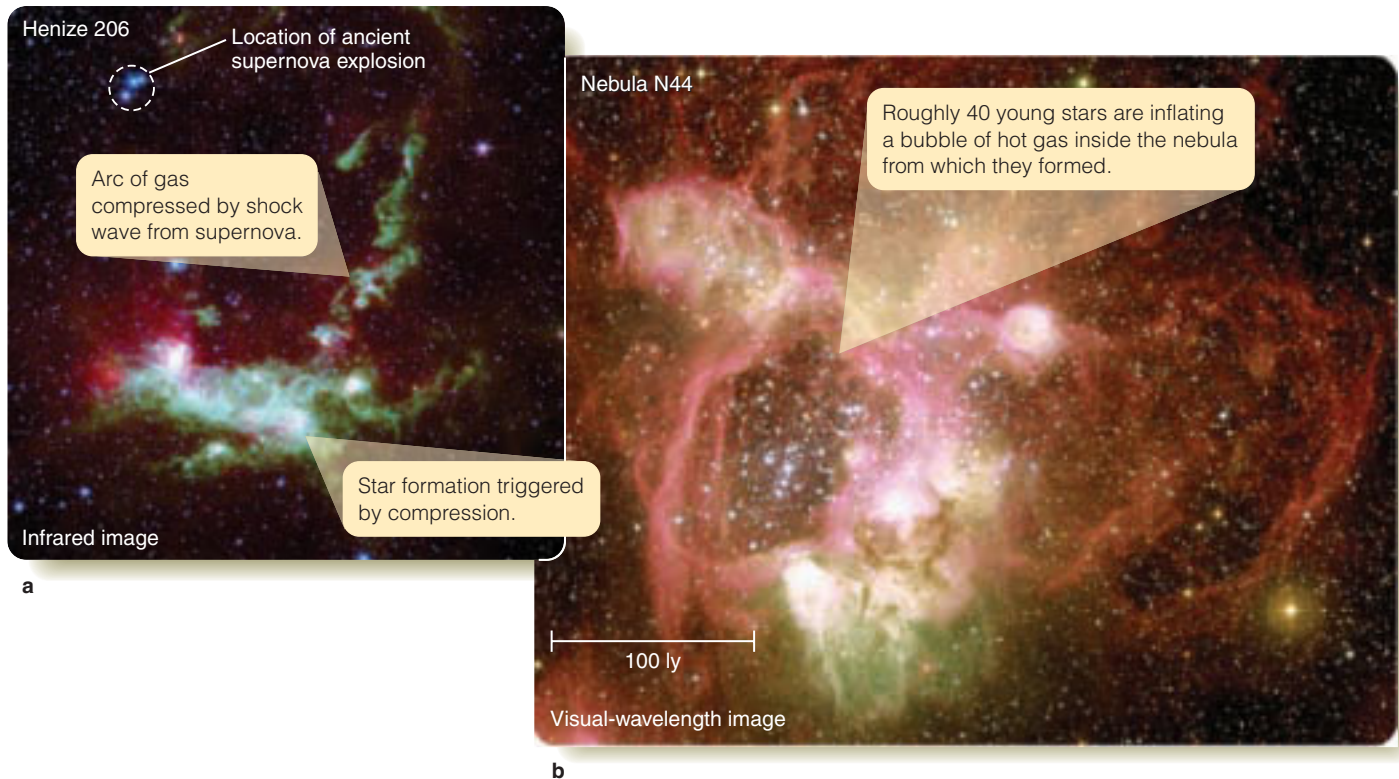
Shock Wave Triggers Star Formation



■ **Figure 11-2**

In this summary of a computer model, an interstellar gas cloud is triggered into star formation by a passing shock wave. The events summarized here might span about 6 million years.

Evidently, collapsing clouds break into fragments, and the densest parts form a number of dense cores. Exactly why clouds divide into fragments isn't fully understood, but their rotation, magnetic fields, and turbulence apparently play important roles. Whatever the reason, when a giant cloud of interstellar matter contracts, it forms many newborn stars simultaneously.



■ **Figure 11-3**

(a) An expanding shock wave from a supernova explosion a few million years ago has compressed a nearby cloud of gas and triggered the birth of new stars. Most of the bright, young stars in this arc-shaped nebula are hidden deep in dust clouds and are not yet visible at visual wavelengths. (NASA/JPL-Caltech/V. Gorjian, NOAO) (b) Nebula N44 has given birth to a large cluster of stars. The process of star formation can spread to new regions by the effects of stars already formed. (ESO)

Heating by Contraction

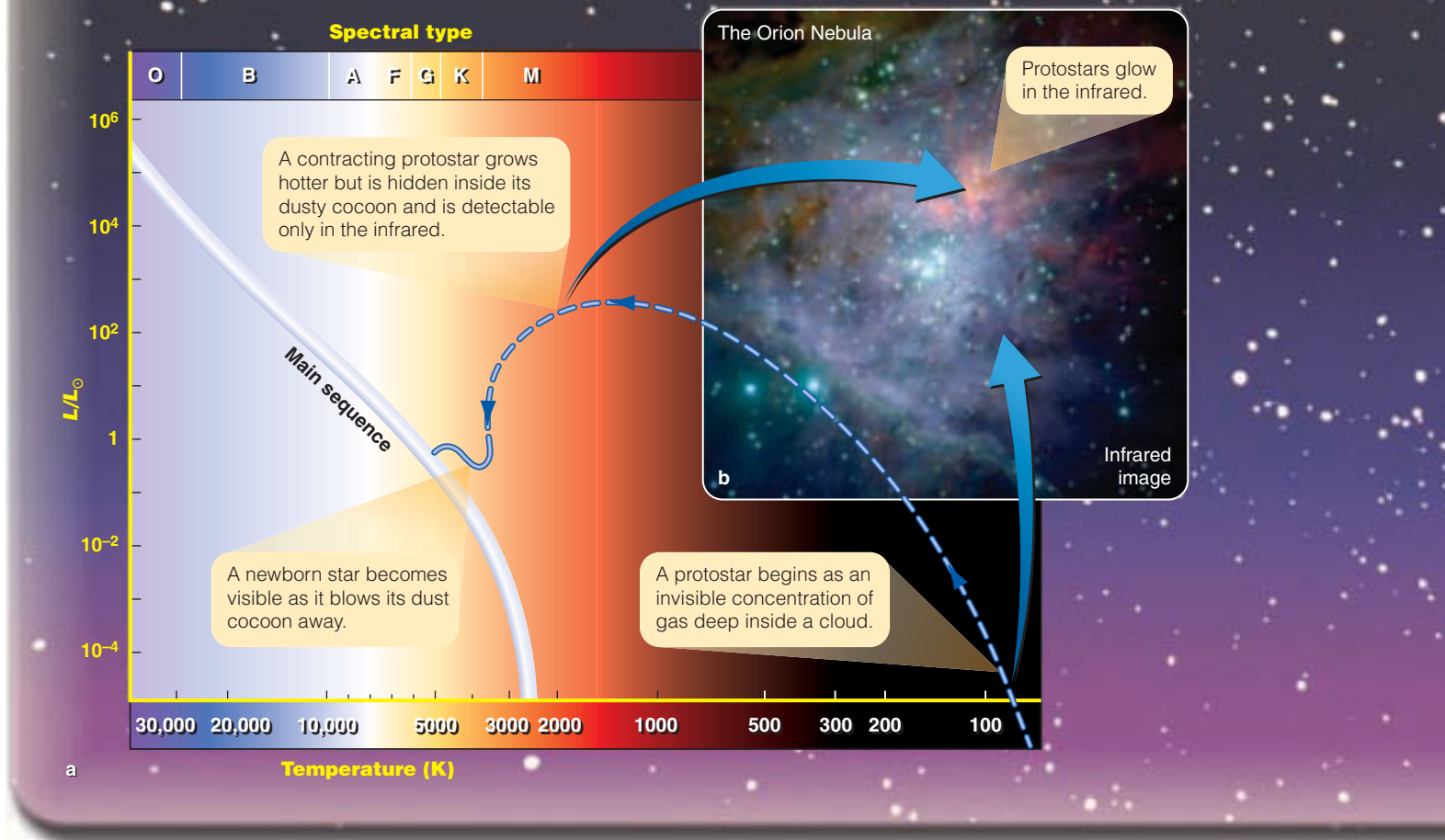
You can understand how low-density clouds of interstellar gas might contract and become dense enough to make stars, but how does the cold gas become hot enough to be a star? The answer, once again, is gravity.

To see how gravity can heat the gas, shift your attention to one dense cloud core destined to become a single star. Once that small cloud of gas begins to contract, gravity draws the atoms toward the center. This means the atoms are falling, and, like all things that fall, they gain speed as they fall. In fact, astronomers refer to this early stage in the formation of a star as **free-fall collapse**. Although the atoms may have been moving slowly to start with, by the time they have fallen most of the way to the center of the cloud, they are traveling rapidly. Thermal energy is the agitation of the particles in a gas, so this increase in speed is a step toward heating the gas. However, you can't say that the gas is hot simply because all of the atoms are moving fast. The air in the cabin of a jet airplane is traveling rapidly, but it isn't hot because all of the atoms are moving in generally the same direction along with the plane. The high speed of the infalling atoms is not converted into thermal energy until their motion becomes randomized, and that happens when the atoms begin to collide with one another as they fall into the central region of the cloud. The

jumbled, random, rapid motion of the colliding atoms represents thermal energy, and so the temperature of the gas increases.

This is an important principle in astronomy. Whenever a cloud of gas contracts, the atoms move “downward” in the gravitational field, pick up speed, and collide more rapidly, and the gas grows hotter. Astronomers express this by saying that gravitational energy is converted into thermal energy. Whenever a gas cloud expands, gas atoms move “upward” against gravity and lose speed, and the gas becomes cooler. Astronomers say that in this case thermal energy is converted into gravitational energy. The principle applies not only to clouds of interstellar gas but also to contracting and expanding stars, as you will see in the following chapters.

Earlier you learned that thermal energy in random atomic motion is one of the factors that can resist gravity and keep a cloud from contracting. So, you may ask, does the contraction stop once the free-fall collapse heats the gas? The answer is no, not if there is a way for the compressed cloud to get rid of some thermal energy by radiating it away. The contracting cloud is still relatively cold; and, according to Wien's law (see Chapter 7), its material should produce very-long-wavelength radiation to which the cloud will be mostly transparent. Thus, some thermal energy generated by the collapse can escape the cloud, and contraction can continue. Astronomers know this happens because they



■ **Figure 11-4**

(a) This H–R diagram has been extended to very low temperatures to show schematically the contraction of a dim, cool protostar. (Illustration design by M. Seeds) (b) Protostars are normally invisible at visual wavelengths because they are cool objects and are deep inside dusty clouds of gas, but they are detectable at infrared wavelengths. (ESO)

observe far-infrared spectral emission lines, called **cooling lines**, from dense cloud cores that are evidently contracting.

Your study of gas clouds has shown how the contraction of dense cores in giant molecular clouds can begin and how this contraction heats the gas. Now you are ready to construct a detailed story of the transformation from gas cloud to star.

Protostars

To understand star formation further, you can continue to follow the contraction of a dense core as matter falls in and heats up, and the object gradually behaves more and more like a star. When the contracting core becomes hot enough, it produces short-wavelength radiation to which the core is not transparent. Then the core's thermal energy can no longer escape, and it enters a new stage of slow, rather than free-fall, contraction. Although the term is used rather loosely by astronomers, a **protostar** can be defined as a prestellar object that is compressed enough that it is opaque at all wavelengths but not so hot and compressed as to be able to generate energy by nuclear fusion, as would a main-sequence star.

Instead, a protostar shines with energy released gravitationally, from a combination of matter falling inward to the protostar plus slow contraction of the protostar itself.

Early in its life a protostar develops a higher-density region at the center and a low-density outer region, or envelope, because the material that started falling in from closer to the center races ahead of material falling from farther out. Meanwhile, material continues to flow inward from the outer parts of the cloud. In other words, the cloud contracts from the inside out, with the protostar growing deep inside a surrounding cloud of cold, dusty gas.

These enveloping clouds have been called **cocoons** because they hide the forming protostar from view. That is especially true for observations at short wavelengths. The cocoon absorbs the protostar's radiation and, growing warm, reradiates the energy as longer-wavelength infrared radiation than the radiation produced by the protostar. In other words, if you observe at short infrared wavelengths, you may be able to observe the protostar itself; at longer wavelengths, you might be able to observe its envelope. In either case, what you detect would be cooler than a star but much larger than the sun and would therefore be a very luminous infrared source, with properties placing it in the upper right part of the H–R diagram (■ Figure 11-4).

The theory of star formation takes you into an unearthly realm filled with unfamiliar processes and objects. How can anyone really know how stars are born? Although the theory of star

Theories and Proof

How do astronomers know the sun isn't made of burning coal? People say dismissively of a theory they dislike, "That's only a theory," as if a theory were just a random guess. A hypothesis is something like a guess, but of course not a random one. What scientists mean by the word *theory* is a hypothesis that has "graduated" to being confidently considered a well-tested truth. You can think of a hypothesis as equivalent to having a suspect in a criminal case and a theory as equivalent to having finished the trial and having convicted someone of the crime.

Of course, no matter how many tests and experiments you conduct, you can never prove that any scientific theory is absolutely true. It is always possible that the next observation you make will disprove the theory. And it is unfortunately sometimes true that innocent people go to jail and guilty people are free, but, occasionally, with further evidence, those legal mistakes can be fixed.

There have always been hypotheses about why the sun is hot. Some scientists once thought the sun was a ball of burning coal. Only a century ago, most astronomers accepted the hypothesis that the sun was hot because gravity was making it contract. In the late 19th century, geologists showed that Earth

was much older than the sun could be if it was powered by gravity, so the gravity hypothesis had to be wrong. It wasn't until 1920 that a new hypothesis was proposed by Sir Arthur Eddington, who suggested that the sun is powered somehow by the energy in atomic nuclei. In 1938 the German-American astrophysicist Hans Bethe showed how nuclear fusion could power the sun. He won the Nobel Prize in 1967.

The fusion hypothesis is now so completely confirmed that it is fair to call it a theory. No one will ever go to the center of the sun, so you can't *prove* the fusion theory is right. Many observations and model calculations support this theory, and in Chapter 8 you saw further evidence in the neutrinos that have been detected coming from the sun's core. Nevertheless there remains some tiny possibility that all the observations and models are misunderstood and that the theory will be overturned by some future discovery. Astronomers have tremendous confidence that the sun is powered by fusion and not gravity or coal, but a scientific theory can never be proven conclusively correct.

There is a great difference between a theory in the colloquial sense of a far-fetched guess and a scientific theory that has undergone decades of testing and confirmation with



Technically it is still a theory, but astronomers have tremendous confidence that the sun gets its power from nuclear fusion and not from burning coal. (SOHO/MDI)

observations, experiments, and models. But no theory can ever be proven absolutely true. It is up to you as a consumer of knowledge and a responsible citizen to distinguish between a flimsy guess and a well-tested theory that deserves to be treated like truth—at least pending further information.

formation, like all scientific theories, can never be absolutely proven, scientists have strong confidence in it because of repeated testing by observation (**How Do We Know? 11-1**). There is plenty of evidence that star formation is a continuous process; you can be sure that stars are being born right now.

11-2 The Orion Nebula: Evidence of Star Formation

IN ASTRONOMY, evidence means observations. Consequently, you can ask what observations confirm the hypotheses about star formation. Protostars are not easy to observe. Astronomers calculate that the protostar stage is only a few tenths of a percent of the lifetime of a star like the sun; and, although that is a long time in human terms, you cannot expect to catch many stars in the protostar stage. Furthermore, protostars form deep inside clouds of dusty gas that block your view at visible wavelengths, and, being cooler than full-fledged stars, they produce radiation primarily at longer wavelengths. Astronomers must therefore

depend on observations at infrared and radio wavelengths to search for protostars in their natural environment.

On a clear winter night, you can see with an unaided eye the Great Nebula of Orion as a fuzzy blob in Orion's sword. With binoculars or a small telescope, it is striking, and through a large telescope, it is breathtaking. At the center of the nebula lie four brilliant blue-white stars known as the Trapezium, the brightest in a cluster of a few hundred stars. Surrounding the stars are the glowing filaments of a nebula more than 8 pc across. Like a great thundercloud illuminated from within, the churning currents of gas and dust suggest immense power. The significance of the Orion Nebula, also known as Messier 42, lies hidden, figuratively and literally, beyond the visible nebula. This region is ripe with star formation.

Observing Star Formation

Observations provide plenty of evidence that star formation is a continuous process; you can be sure that stars are being born right now. Read **Star Formation in the Orion Nebula** on pages 216–217 and note four important points and one new term:

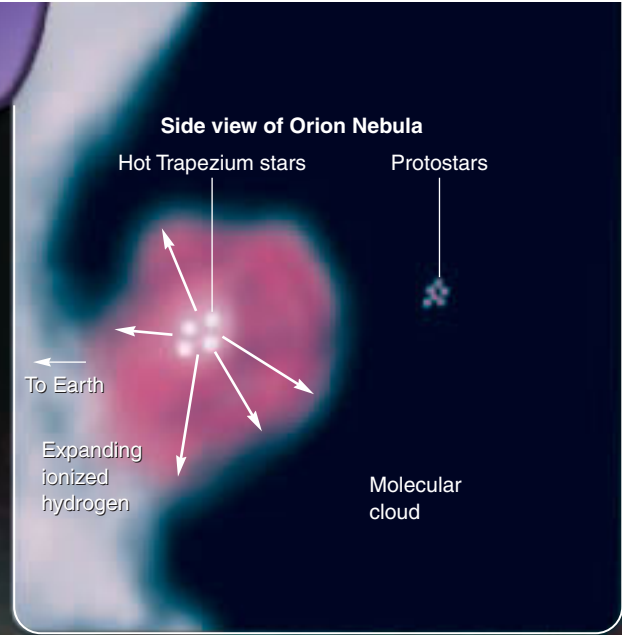
- 1 The nebula you see is only a small part of a vast, dusty molecular cloud. You see the nebula because the larger stars

Star Formation in the Orion Nebula

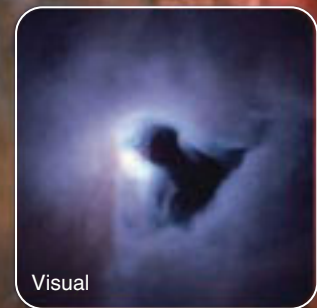
1 The visible Orion Nebula shown below is a pocket of ionized gas on the near side of a vast, dusty molecular cloud that fills much of the southern part of the constellation Orion. The molecular cloud can be mapped by radio telescopes. To scale, the cloud would be many times larger than this page. As the stars of the Trapezium were born in the cloud, their radiation has ionized the gas and pushed it away. Where the expanding nebula pushes into the larger molecular cloud, it is compressing the gas (see diagram at right) and may be triggering the formation of the protostars that can be detected at infrared wavelengths within the molecular cloud.

Hundreds of stars lie within the nebula, but only the four brightest, those in the Trapezium, are easy to see with a small telescope. A fifth star, at the narrow end of the Trapezium, may be visible on nights of good seeing.

The cluster of stars in the nebula is less than 2 million years old. This must mean the nebula is similarly young.



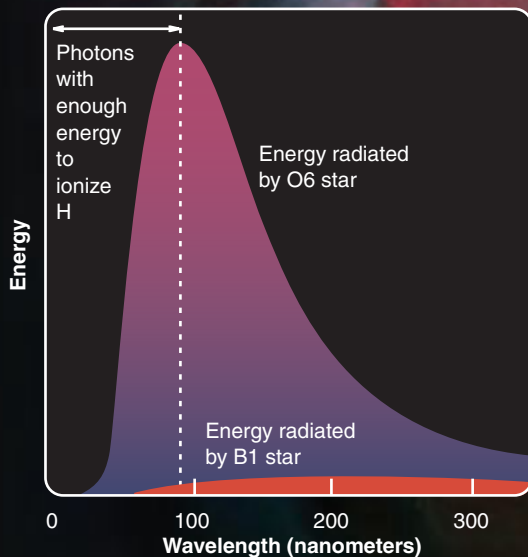
The near-infrared image above reveals more than 50 low-mass, cool protostars.



Small dark clouds called **Bok globules**, named after astronomer Bart Bok, are found in and near star-forming regions. The one pictured above is part of nebula NGC 1999 near the Orion Nebula. Typically about 1 light-year in diameter, they contain from 10 to 1000 solar masses.

Visual-wavelength image

Credit: NASA, ESA, M. Robberto, STScI and the Hubble Space Telescope Orion Treasury Project Team

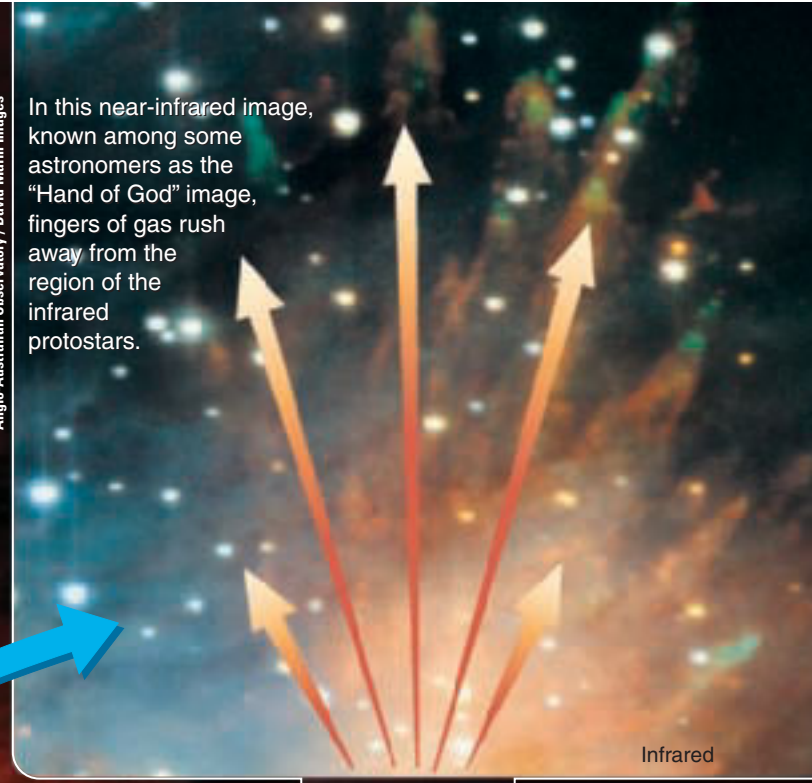


2 Of all the stars in the Orion Nebula, only one is hot enough to ionize the gas. Only photons with wavelengths shorter than 91.2 nm can ionize hydrogen. The second-hottest stars in the nebula are B1 stars, and they emit little of this ionizing radiation. The hottest star, however, is an O6 star 30 times the mass of the sun. At a temperature of 40,000 K, it emits plenty of photons with wavelengths short enough to ionize hydrogen. Remove that one star, and the nebula would turn off its emission.

3 Below, a far-infrared image has been combined with an ultraviolet and visible image to reveal extensive nebulosity surrounding the visible Orion Nebula. Red and orange show the location of cold, carbon-rich gas molecules. Green areas outline hot, ionized gas around young stars. The infrared image reveals protostars buried in the gas cloud behind the visible nebula.

Anglo-Australian Observatory / David Malin Images

In this near-infrared image, known among some astronomers as the "Hand of God" image, fingers of gas rush away from the region of the infrared protostars.



Infrared

Dan Gezari, Dena Backman, and Mike Werner

Infrared image

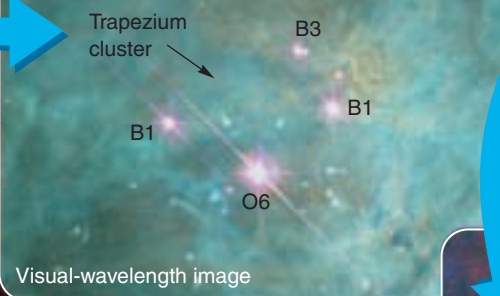


The Becklin-Neugebauer object (BN) is a hot B star just reaching the main sequence. It is not detectable at visual wavelengths. The Kleinmann-Low nebula (KL) is a cluster of cool young protostars also detectable only in the infrared.

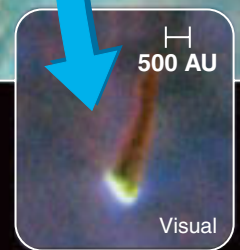
The Becklin-Neugebauer object (BN) is a hot B star just reaching the main sequence. It is not detectable at visual wavelengths. The Kleinmann-Low nebula (KL) is a cluster of cool young protostars also detectable only in the infrared.

NASA

The spectral types of the Trapezium stars are shown here. The gas looks green because of filters used to record the image.



Visual-wavelength image



Visual

NASA

4 As many as 85 percent of the stars in the Orion Nebula are surrounded by disks of gas and dust. One such disk is seen at the upper right of this Hubble Space Telescope image, magnified in inset. Radiation from the nearby hot Trapezium stars is evaporating gas from the disk and driving it away to form an elongated nebula.

Ultraviolet + visible + infrared image

born within it have ionized the gas and driven it outward, breaking out of the molecular cloud. Visual and infrared observations reveal small dusty clouds of gas called *Bok globules* that may be in the process of forming stars.

- 2 A single very hot and short-lived O star is almost entirely responsible for producing the ultraviolet photons that ionize the gas and make the nebula glow. This star is so massive that it has already become a main sequence star while its smaller siblings are still protostars.
- 3 Infrared observations reveal clear evidence of active star formation deeper in the molecular cloud behind the visible nebula.
- 4 Many of the young stars in the Orion nebula are surrounded by disks of gas and dust.

You should not be surprised to find star formation in Orion. The constellation is a brilliant pattern in the winter sky, marked by bright blue stars. Although those stars are hundreds of parsecs away, they appear bright because they are tremendously luminous. Such high-luminosity O and B stars cannot live more than a few million years. That is an astronomically short time, and they are not moving quickly, so they must have been born somewhere near where you see them now.

Are there other nebulae like the Orion Nebula? Such emission nebulae are actually quite common, and many examples shown in this chapter as well as in the previous chapter are produced by newborn stars just as is the Orion Nebula. The shape of a nebula is determined, in part, by the distribution of gas around the forming stars. The nebula around the star cluster NGC 602 is strikingly similar in shape to the Orion Nebula (■ Figure 11-5).

Contagious Star Formation

Not only can astronomers locate evidence of star formation, but they have also found evidence that star formation can stimulate more star formation. If a gas cloud produces massive stars, those massive stars ionize the gas nearby and drive it away. Where the intense radiation and hot gas pushes into surrounding gas, it can compress the gas and trigger more star formation. One sign of this process is the presence of **star-formation pillars**, columns of gas that point back toward the young massive star. Such pillars are produced by denser regions of clouds that protect the gas behind them as the blast of intense radiation and hot gas flows past (■ Figure 11-6). Another way massive stars can trigger further star formation is by exploding as a supernova. You read earlier in this chapter how such an explosion can drive a shock wave through surrounding gas and cause interstellar clouds to collapse, forming new stars (Figure 11-3a).

Like a brush fire moving through the interstellar medium, star formation can spread itself especially by creating massive stars, and astronomers have located the remains of such episodes



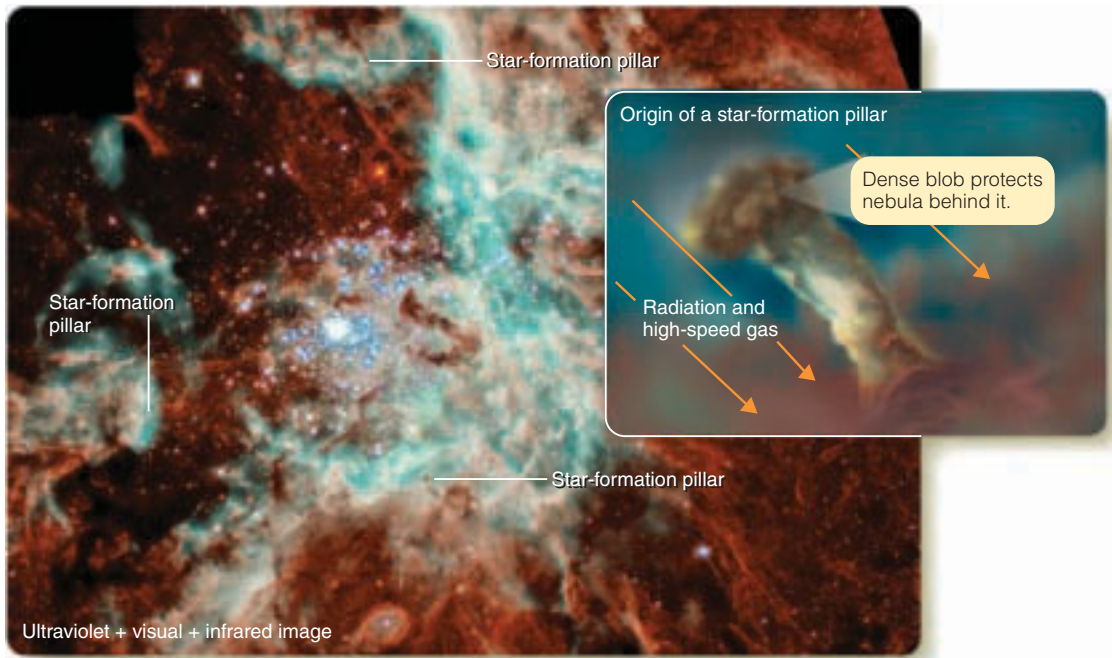
■ **Figure 11-5**

The nebula around star cluster NGC 602 resembles the Orion Nebula. It has been inflated by radiation and winds streaming away from the cluster of hot young stars at lower right. More stars are forming where gas is compressed at upper left. (NASA/ESA, and the Hubble Heritage Team)

(■ Figure 11-7). Of course, lower-mass stars also form in the process, but they cannot trigger further star formation because they are not hot enough to ionize and drive away large amounts of gas, nor do they explode as supernovae.

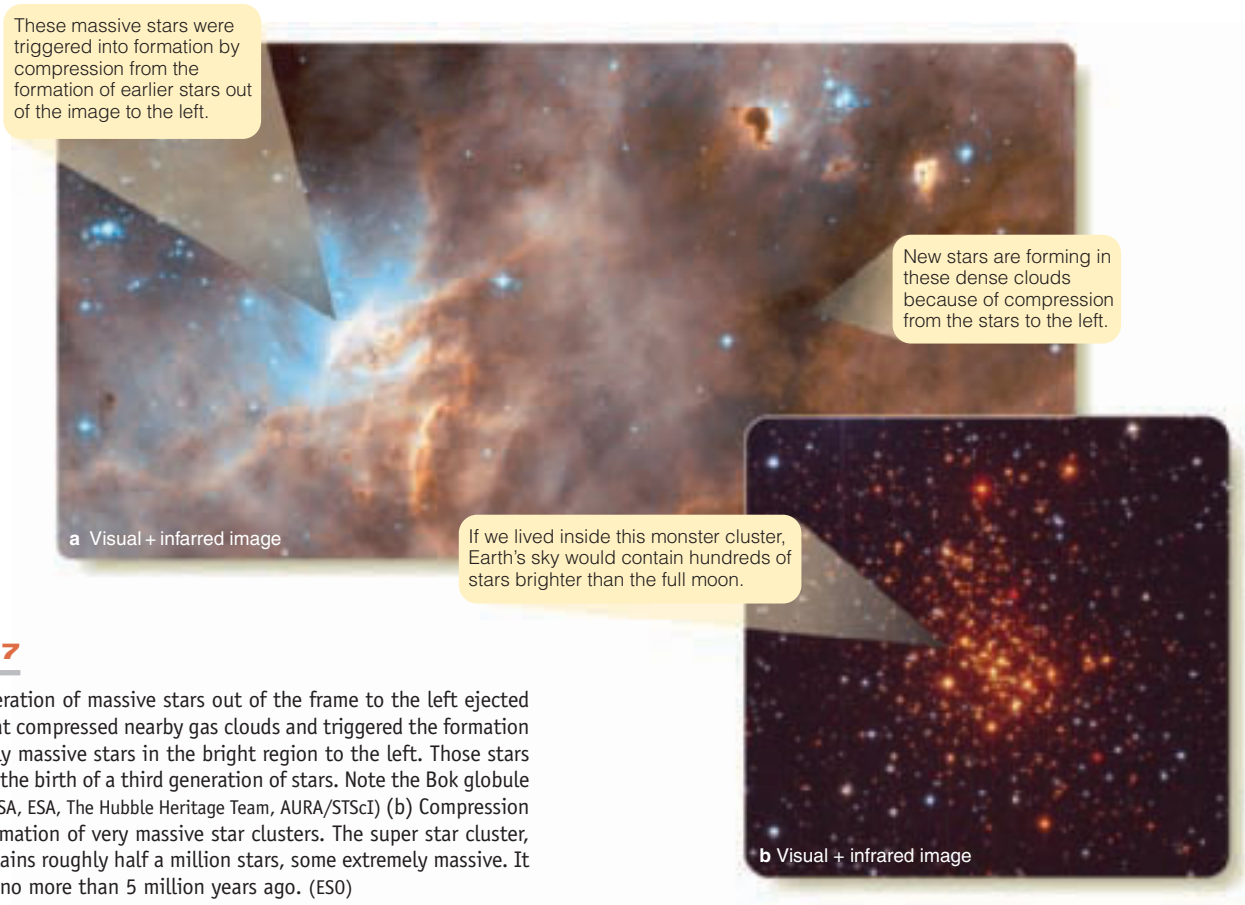
The history of star formation in the constellation of Orion is written in its stars. Judging from the luminosities and estimated masses of the most prominent examples, the stars at Orion's west shoulder are less than 12 million years old, while the stars of Orion's belt are at most 8 million years old. The stars of the Trapezium at the center of the Great Nebula are no older than 2 million years. Star formation has swept across Orion from northwest to southeast, apparently beginning near Orion's west shoulder. The massive stars that formed there probably triggered the formation of the stars in Orion's belt. That star formation episode may then have caused the formation of the new stars you see today in the Great Nebula.

In the next million years, the familiar outline of the Great Nebula will change, and a new nebula may begin to form as the protostars embedded in a different part of the molecular cloud ionize the gas, drive it away, and become visible. Throughout the cloud, centers of star formation may develop and then dissipate as massive stars are born and force the gas to expand. If enough massive stars are born, they could blow the entire molecular cloud apart and bring the successive generations of star formation to a conclusion. The Great Nebula in Orion and its adjacent huge, but invisible, molecular cloud are a beautiful and dramatic example of the continuing cycles of star formation.



■ **Figure 11-6**

The hot, massive stars in the star cluster 30 Doradus are pouring out intense ultraviolet radiation and powerful winds of hot gas that are pushing back and compressing the surrounding nebula. Slightly denser regions in the nebula protect the gas behind them to make star-formation pillars a few light-years long that point back at the star cluster. The dense blobs are being compressed and may make more stars within the next few million years. (N. Walborn and J. Maiz- Apellániz, STScI, R. Barbá, La Plata Observatory, and NASA)



■ **Figure 11-7**

(a) An earlier generation of massive stars out of the frame to the left ejected high-speed gas that compressed nearby gas clouds and triggered the formation of young, extremely massive stars in the bright region to the left. Those stars are now triggering the birth of a third generation of stars. Note the Bok globule at upper right. (NASA, ESA, The Hubble Heritage Team, AURA/STScI) (b) Compression can trigger the formation of very massive star clusters. The super star cluster, Westerlund 1, contains roughly half a million stars, some extremely massive. It must have formed no more than 5 million years ago. (ESO)

SCIENTIFIC ARGUMENT

What did Orion look like to the ancient Egyptians, to the first humans, and to the dinosaurs?

Scientific arguments can do more than support a theory; they can change the way you think of the world around you. The Egyptian civilization had its beginning only a few thousand years ago, and that is not very long in terms of the history of Orion. The stars you see in the constellation are hot and young, but they are a few million years old, so the Egyptians saw the same constellation you see. (They called it Osiris.) Even the Orion Nebula hasn't changed very much in a few thousand years, and Egyptians viewed it in the dark skies along the Nile and perhaps wondered about it.

Our oldest human ancestors lived about four million years ago, and that was about the time that the youngest stars in Orion were forming. These earliest ancestors may have looked up and seen some of the stars you see, but some stars have formed since that time. The Great Nebula is excited by the Trapezium stars, and they are no more than about two million years old, so our earliest human relatives probably didn't see the Great Nebula.

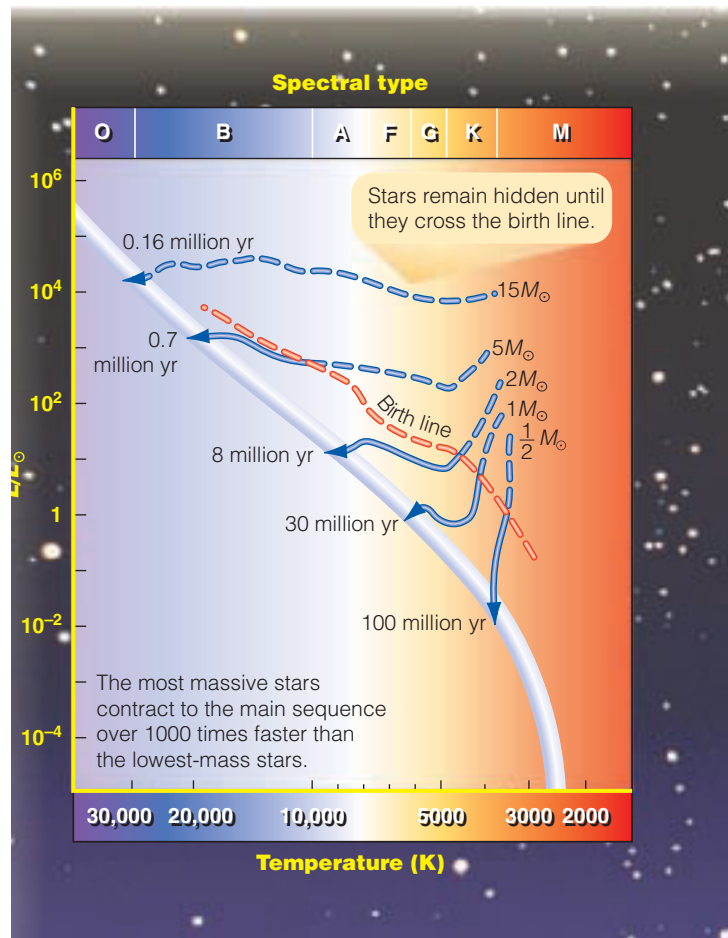
The dinosaurs saw something quite different. The last of the dinosaurs died about 65 million years ago, long before the birth of the brightest stars in Orion. The dinosaurs, had they the brains to appreciate the view, might have seen bright stars along the Milky Way, but they didn't see Orion. All of the stars in the sky are moving through space, and the sun is orbiting the center of our galaxy. Over many millions of years, the stars move appreciable distances across the sky. The night sky above the dinosaurs contained totally different star patterns.

The Orion Nebula is the product of a giant molecular cloud, but such a cloud can't continue spawning new stars forever. Focus your argument to answer the following: **What processes limit star formation in a molecular cloud?**

11-3 Young Stellar Objects and Protostellar Disks

WHEN MOST OF THE MATERIAL in a protostar's cocoon has fallen inward or been driven away, the protostar will no longer be quite so hidden. The locations in the H-R diagram of protostars that have become detectable at visible wavelengths because their cocoons have disappeared is called the **birth line** (■ Figure 11-8). Once a star crosses the birth line and becomes visible, it continues to contract and move toward the main sequence at a pace that depends on its mass. Stars in this late stage of formation are sometimes called **Young Stellar Objects (YSOs)** or pre-main-sequence stars, to distinguish them from earlier protostellar stages.

The more massive a star, the stronger its gravity and therefore the more rapid will be its contraction. Astronomers calculate that the sun took about 30 million years from when its cloud began contracting until it became a main-sequence star, but a 30-solar-mass star would take only 30,000 years. A 0.2-solar-mass star needs as much as 1 billion years to finish forming and reach the main sequence.



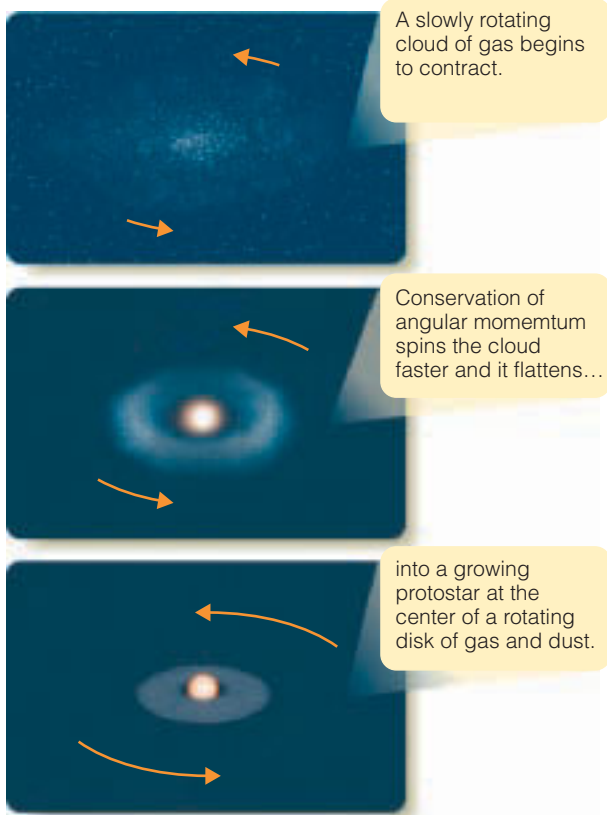
■ Figure 11-8

The more massive a protostar is, the faster it contracts. A $1-M_{\odot}$ star requires 30 million years to reach the main sequence. (Recall that M_{\odot} means "solar mass.") The dashed line is the birth line, where contracting protostars first become visible as they dissipate their surrounding clouds of gas and dust. Compare with Figure 11-4, which shows the evolution of a protostar of about $1 M_{\odot}$ as a dashed line up to the birth line and as a solid line from the birth line to the main sequence. (Illustration design by M. Seeds)

As a contracting molecular cloud core becomes a protostar, the cloud rotates faster and faster. The rapidly spinning core of the cloud must flatten into a spinning disk like a blob of pizza dough spun into the air. Gas from the envelope that has lost its angular momentum through collisions can sink directly to the center of the cloud, where the protostar grows larger, surrounded by the disk. Other infalling material can add to the disk and then move within the disk plane toward the star. Astronomers calculate that this material gives up much of its angular momentum via collisions in the disk and possibly also by interactions with the disk's magnetic field, before sinking into the protostar (■ Figure 11-9).

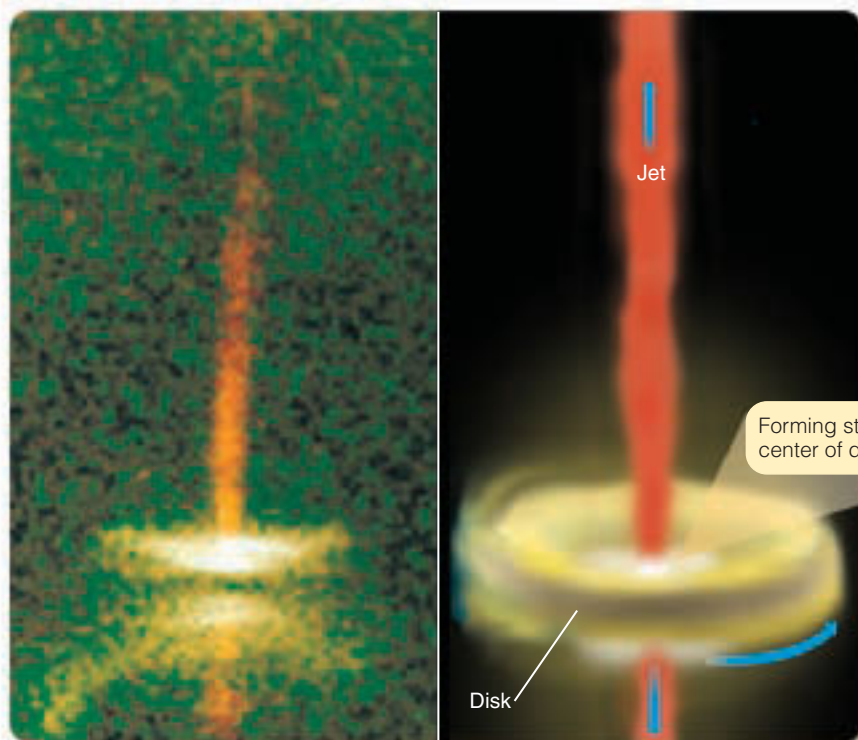
Theoretically, for a protostar to have no surrounding disk at all, its original cloud would need to have zero angular momentum, which is very unlikely. Observationally, astronomers find that the majority of protostars appear to be surrounded by disks. The disks that form around protostars are called **protostellar disks**, and they are important because, as you will learn in

Formation of a Protostellar Disk



■ **Figure 11-9**

The rotation of a contracting gas cloud forces it to flatten into a disk, and the protostar grows at the center. The scale of the top panel is much larger than the lower two panels.



■ **Figure 11-10**

In the object HH 30, a newly formed star lies at the center of a dense disk of dusty gas that is narrow near the star and thicker farther away. Although the star is hidden from you by the edge-on dusty disk, the star illuminates the inner surface of the disk. Interactions between the infalling material in the disk and the spinning star eject jets of gas along the axis of rotation. The artist's conception on the right is to help interpret what you see in the Hubble Space Telescope image on the left. (C. Burrows, STScI & ESA, WFPC 2 Investigation Definition Team, NASA)

Chapter 19, astronomers conclude that planets form within these disks. In fact, the evidence indicates that Earth formed in such a disk around the protosun 4.6 billion years ago. Because most protostars have protostellar disks, it seems likely that most stars have planetary systems.

Read **Observational Evidence of Star Formation** on pages 222–223 and notice that it makes four important points and introduces three new terms:

- 1 Star formation regions contain types of stars so young they must have formed recently. *T Tauri* stars, for example, are a type of star understood to still be in the slowly contracting phase.
- 2 Infrared observations reveal the complicated shapes of star-forming clouds that are strongly affected by radiation and winds from nearby luminous stars.
- 3 In the H–R diagram, newborn stars lie between the birth line and the main sequence—just where you would expect to find stars that have recently lost their dust cocoons. Young stars tend to have very active, hot coronae and chromospheres, making them prominent X-ray sources.
- 4 Observations provide clues about the effects of disks of gas and dust around protostars. These disks evidently cause *bipolar flows* that push into the surrounding interstellar medium and produce glowing blobs called *Herbig–Haro objects*. Images have been obtained of a few protostellar disks. Astronomers have abundant evidence that these disks are the sites of planet formation.

In some cases, these dark disks of gas and dust are clearly visible around newborn stars (■ Figure 11-10), but it isn't clear how the protostellar disk produces jets. Certainly the contracting, spinning disk contains tremendous energy, and theorists suspect that magnetic fields

Observations of Young Stellar Objects and Protoproctellar Disks

1 The nebula around the star S Monocerotis is bright with hot stars. Such stars live short lives of only a few million years, so they must have formed recently. Such regions of young stars are common. The entire constellation of Orion is filled with young stars and clouds of gas and dust.

Nebulae containing young stars usually contain **T Tauri** stars. These stars fluctuate irregularly in brightness, and many are bright in the infrared, suggesting they are surrounded by dust clouds and in some cases by dust disks. Doppler shifts show that gas is flowing away from many T Tauri stars. The T Tauri stars appear to be newborn stars just blowing away their dust cocoons. T Tauri stars have ages ranging from 100,000 years to 100,000,000 years. Spectra of T Tauri stars show signs of an active chromosphere as we might expect from young, rapidly rotating stars with powerful dynamos and strong magnetic fields.



Visual

Skyfactory.org



Infrared

NASA/JPL-Caltech/W. Reach

2 The Elephant Trunk (above) is a dark nebula compressed and twisted by radiation and winds from a luminous star beyond the left edge of this image. Infrared observations reveal that it contains six protostars (pink objects, lower edge) not detected at visual wavelengths.

Visual-wavelength image

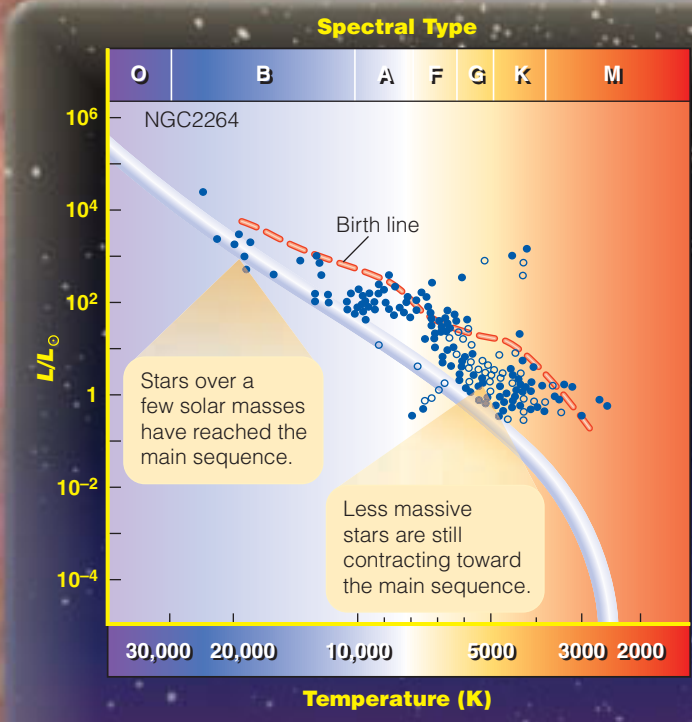


X-ray

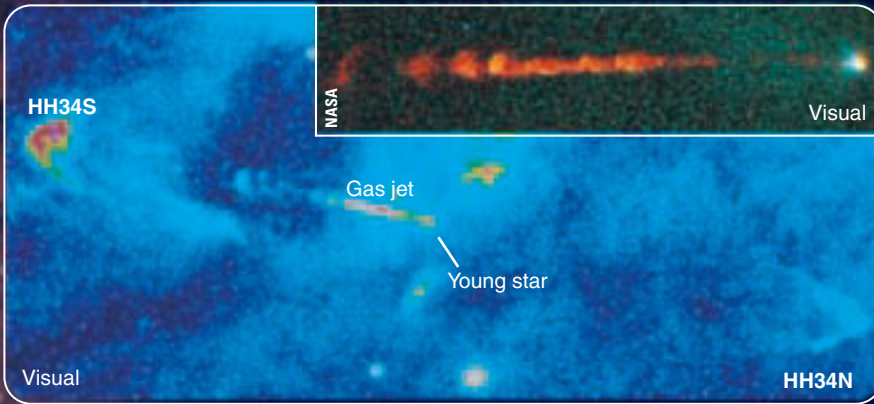
NASA/CXC/SAO

Roughly 1000 young stars with hot chromospheres appear in this X-ray image of the Orion Nebula.

3 The star cluster NGC 2264, imbedded in the nebula on this page, is only a few million years old. Lower-mass stars have not yet reached the main sequence, and the cluster contains many T Tauri stars (open circles), which are found above and to the right of the main sequence, near the birth line. The faintest stars in the cluster were too faint to be observed in this study.

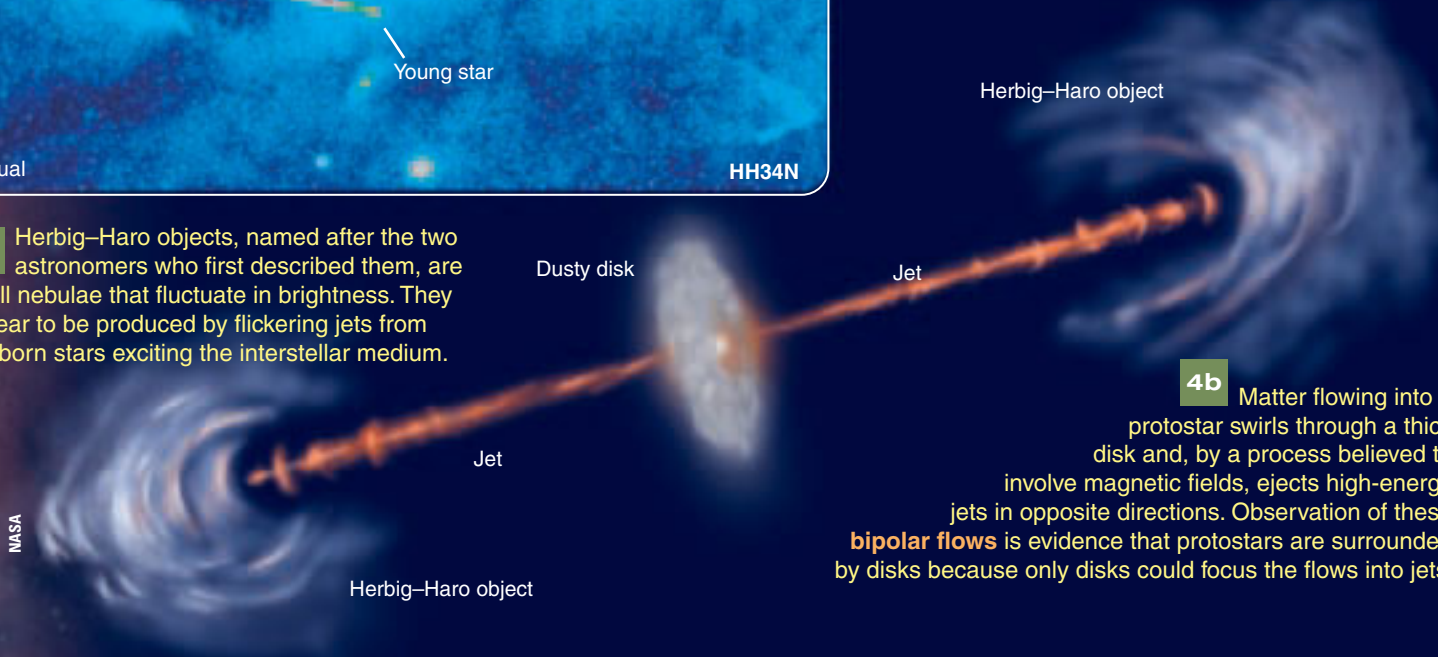


Richard Mundt, Calar Alto 3.5 m telescope

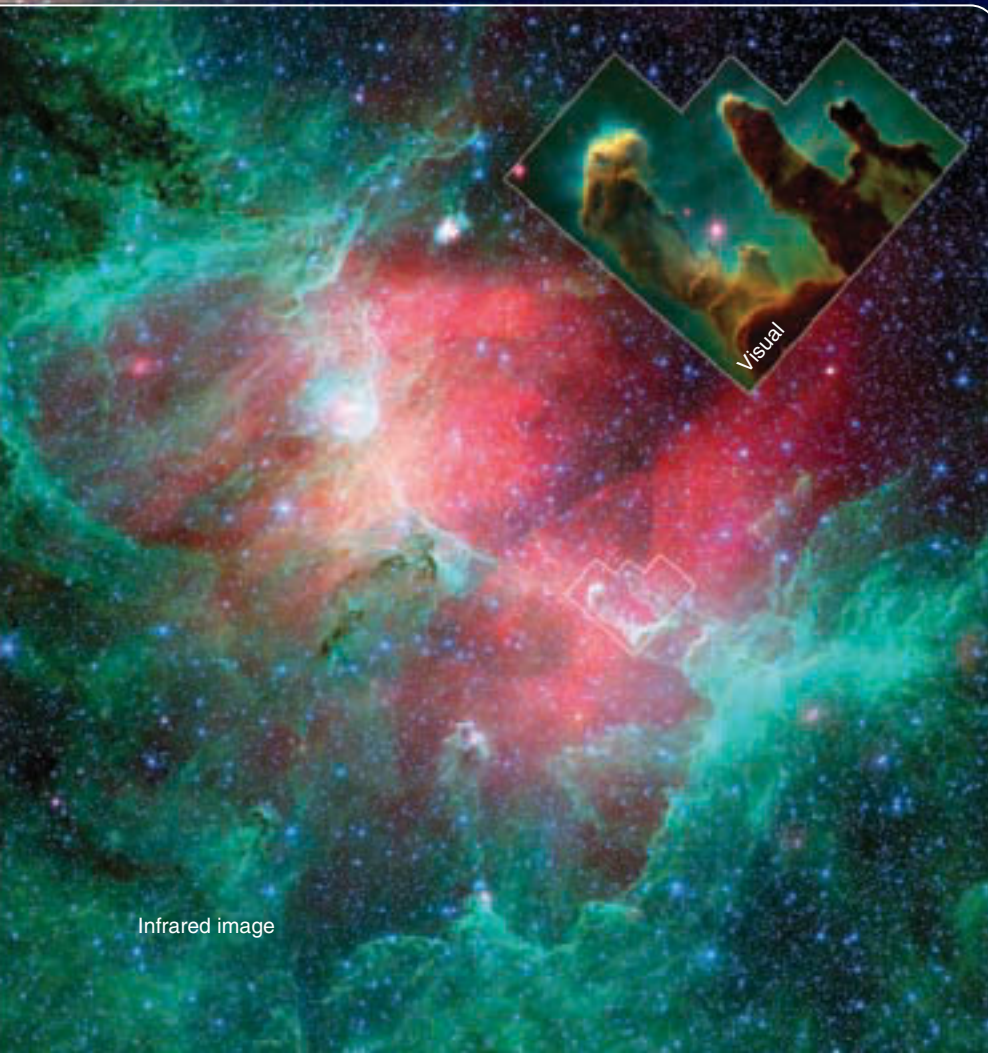


4 At the center of this image, a newborn star is emitting powerful jets to left and right. Where the jets strike the interstellar medium, they produce **Herbig-Haro objects**. The inset shows how irregular the jet is. Such jets can be over a light-year long and contain gas traveling at 100 km/s or more.

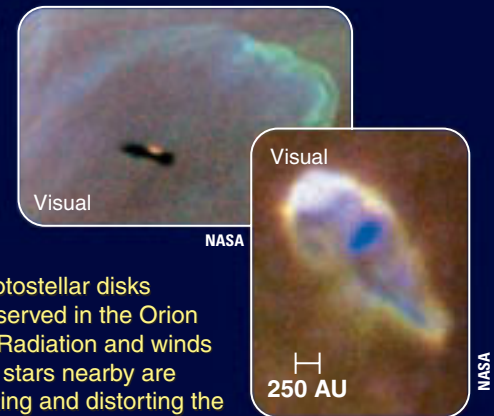
4a Herbig-Haro objects, named after the two astronomers who first described them, are small nebulae that fluctuate in brightness. They appear to be produced by flickering jets from newborn stars exciting the interstellar medium.



4b Matter flowing into a protostar swirls through a thick disk and, by a process believed to involve magnetic fields, ejects high-energy jets in opposite directions. Observation of these **bipolar flows** is evidence that protostars are surrounded by disks because only disks could focus the flows into jets.



4c Radiation and winds from massive stars have shaped this nebula, Messier 16, and a recent supernova has heated some of the dust (red). Shock waves from the explosion will destroy the Eagle Nebula star-formation pillars (inset) within about 1000 years. Erosion of part of the Eagle Nebula has exposed small fingers and globules of denser gas. About 15 percent of those have formed protostars.



4d Protostellar disks observed in the Orion Nebula. Radiation and winds from hot stars nearby are evaporating and distorting the disks. The disk pictured right is above is seen silhouetted against the nebula, with light from the protostar embedded in the disk's center apparent at its upper edge. Although bigger than the present size of our solar system, such disks are now understood to be sites of planet formation.

NASA/JPL-Caltech/M. Hägley & A. Noriega-Crespo

Infrared image

become twisted tightly around the disk. Exactly how those fields eject hot gas away from the stars is not completely understood, but the presence of a confining disk is thought to explain why material flows out in two streams along the axis of rotation. The detection of these jets was one of the first pieces of evidence that substantial disks often surround protostars.

Some evidence of stellar youth is not obvious. An **association** is a widely distributed star cluster that is not held together by its own gravity—its stars wander away as the association ages. It is not clear why some gas clouds give birth to compact star clusters held together by their own gravity and others give birth to larger associations not bound together. You can conclude, however, that associations must consist of young stars because the stars wander apart astronomically quickly. The constellation Orion, a known region of star formation, is filled with T Tauri stars in a **T association**. T Tauri stars are relatively low-mass pre-main-sequence objects ranging from roughly 0.5 to 2 solar masses. **OB associations**, fairly obviously, are extended groups of more massive O and B stars. Associations of stars that are journeying away from each other as we watch are clear evidence of recent star formation.

When a protostar becomes hot enough, it can drive away the gas and dust of the protostellar disk as well as any remaining traces of its cocoon. Just as the sun exhales a solar wind, stars produce a **stellar wind**, which can be quite vigorous for hot, young stars. Also, when photons encounter gas atoms or dust specks in space, the photons can exert **radiation pressure**. Stellar winds and radiation pressure combine to blow disks and remnant cocoons apart. As you learned in the previous section, the most luminous stars are even capable of eroding the cocoon and disk material of their neighbors (Figure 11-6). You can recognize that process in the overall shape of the Eagle Nebula (page 223) as well as in the smaller pillars within that nebula.

SCIENTIFIC ARGUMENT

What evidence can you cite that stars in so-called star-forming regions are actually young?

This is a very good example of building a scientific argument because you must cite different forms of evidence to confirm a hypothesis. First, you should note that some extremely luminous stars can't live very long, so when you see such stars, such as the hot blue stars in Orion, you know they must have formed in the last few million years. Many regions of gas and dust contain bright, hot stars that are caught in the act of blowing their nebulae apart; those stars must also have formed recently, or the nebulae would be gone already.

You have other evidence when you look at T Tauri stars. They: (1) are usually associated with interstellar gas and dust concentrations, (2) have H-R diagram locations just above the main sequence where you expect stars to be that are still contracting, and (3) often have protostellar disks that are easily destroyed and cannot last long.

There seems to be no doubt that star formation is an ongoing process, and you can revise your argument to discuss how it happens. **What evidence can you cite that protostars are often surrounded by disks of gas and dust?**

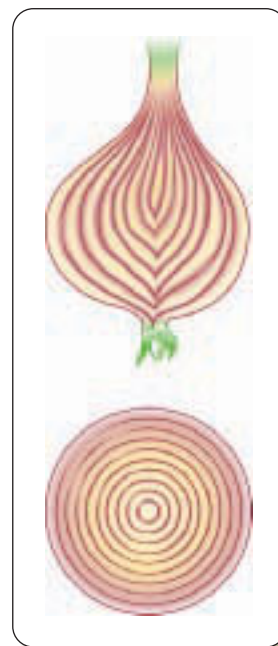
11-4 Stellar Structure

How WOULD YOU go about making a star? It's simple, really. All you need is something, maybe a light-year-sized broom, to gather together a star's mass of interstellar medium, and gravity will do the rest. The object that forms in that way is also simple.

What Keeps a Star Stable?

If there is a single idea in stellar astronomy that can be called crucial, it is the concept of balance. In this section you will discover that stars are held together by their own gravity balanced by the support of their internal heat and pressure. This story will lead your imagination into a region where you yourself can never go—the heart of a star.

Consider the structure of a star, using the basic concept of balance. What is meant here by structure is the variation in temperature, density, pressure, composition, and so on, between the surface of the star and its center. You can think more easily about stellar structure if you imagine that the star is divided into many concentric shells like those in an onion (■ Figure 11-11). You can



■ **Figure 11-11**

To discuss the structure of a star, it is helpful to divide its interior into concentric shells, much like the layers in an onion. This model is, of course, only an aid to your imagination. Stars are not really divided into separable layers.

then focus on the temperature, pressure, and density in each shell. These helpful shells exist only in the imagination; stars do not actually have such separable layers.

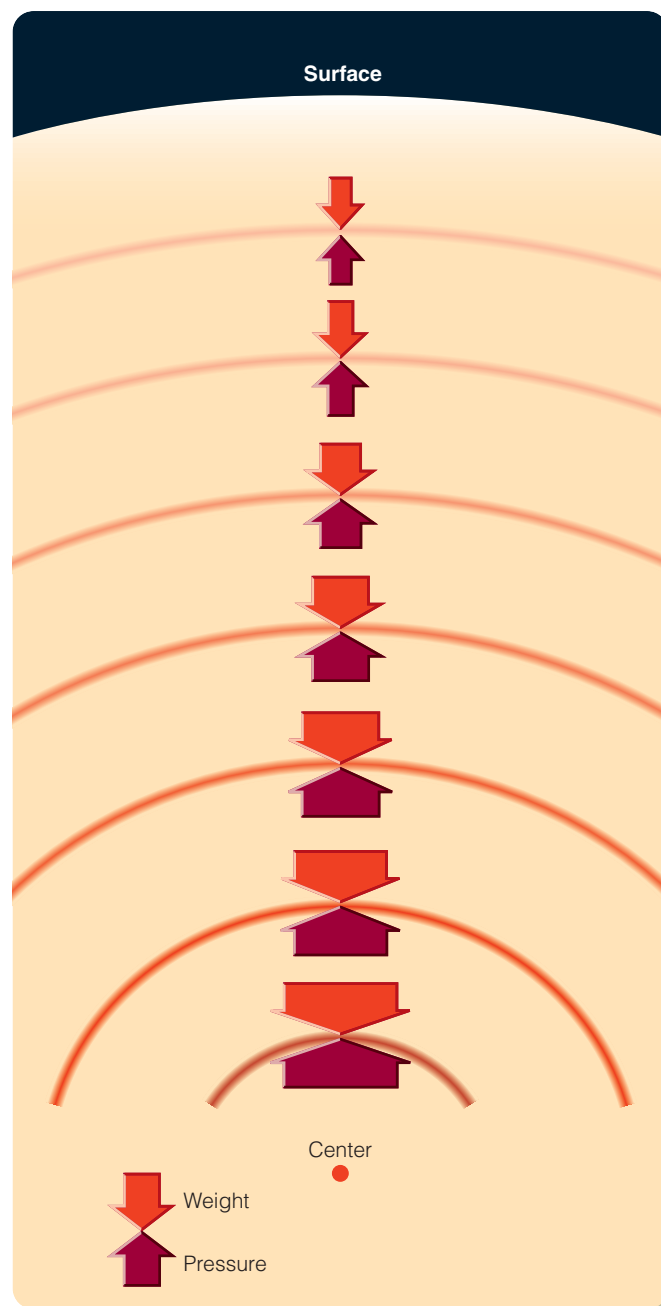
The weight of each layer of a star must be supported by the layer below. (The words *down* or *below* are conventionally used to refer to regions closer to the center of a star.) Picture a pyramid of people in a circus stunt—the people in the top row do not have to hold up anybody else; the people in the next row down are holding up the people in the top row, and so on. In a star that is stable, the deeper layers must support the weight of all of the layers above. The inside of a star is made up of gas, so the weight pressing down on a layer must be balanced by gas pressure in that layer. If the pressure is too low, the weight from above will compress and push down the layer; and if the pressure is too high, the layer will expand and lift the layers above.

This balance between weight and pressure is called **hydrostatic equilibrium**. *Hydro* (from the Greek word for water) tells you the material is a fluid, which by definition includes the gases of a star, and *static* tells you the fluid is stable, neither expanding nor contracting. ■ Figure 11-12 shows this hydrostatic balance in the imaginary layers of a star. The weight pressing down on each layer is shown by lighter red arrows, which grow larger with increasing depth to represent the weight growing larger. The pressure in each layer is shown by darker red arrows. The important point here is that you can be absolutely sure, from this simple argument, that the pressure inside a star must grow larger with increasing depth to support the weight and keep the star stable, even if you can't directly examine the inside of a star.

The pressure in a gas depends on the temperature and density of the gas. Near the surface there is not much weight pressing down, so the pressure does not need to be high for stability. Deeper in the star, the pressure must be higher, which means that the temperature and density of the gas must also be higher. In other words, the principle of hydrostatic equilibrium tells you that stars must have high temperature, pressure, and density inside to support their own weight and be stable. Although the law of hydrostatic equilibrium can tell you some things about the inner structure of stars, you also need to know how energy flows within the star to completely understand its structure.

Energy Transport

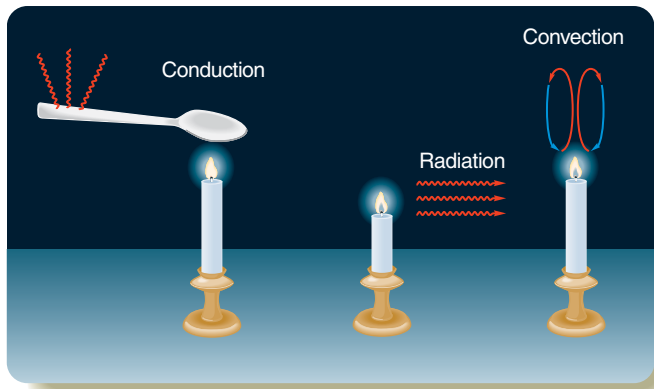
The surface of a star radiates light and heat into space and would quickly cool if that energy were not replaced. Because the inside of the star is hotter than the surface, energy must flow outward to the surface, where it radiates away. This flow of energy through each shell determines its temperature, which, as you saw earlier, determines how much weight that shell can balance. The movement of energy from the inside to the surface of a star thus plays a crucial role in determining the star's structure.



■ **Figure 11-12**

The law of hydrostatic equilibrium says the pressure in each layer must balance the weight on that layer. Consequently, as the weight increases from the surface of a star to its center, the pressure must also increase.

The law of **energy transport** says that energy must flow from hot regions to cooler regions either by conduction, convection, or radiation. Conduction is the most familiar form of heat flow. If you hold the bowl of a spoon in a candle flame, the handle of the spoon grows warmer as heat, in the form of motion among the atoms of the spoon, is conducted from atom to atom up the handle (■ Figure 11-13). But conduction is not a significant cause of



■ **Figure 11-13**

The three modes by which energy may be transported from the flame of a candle, as shown here, are the three modes of energy transport within a star.

heat flow in normal stars because radiation or convection are much more efficient, even in their centers; it is only important in rare types of stars with extremely high densities.

The transport of energy by radiation is another familiar experience. Put your hand near a candle flame, and you can feel the heat. What you actually feel are infrared photons—packets of energy—radiated by the flame and absorbed by your hand. Radiation is the principal means of energy transport in the interiors of most stars. Photons are absorbed and reemitted in random directions over and over as energy works its way from the hot interior toward the cooler surface. The flow of energy by radiation is controlled by the **opacity** of the gas, in other words its resistance to movement of radiation. Opacity in turn depends strongly on the temperature: A hot gas is more transparent, less opaque, than a cool gas.

If the opacity is high, radiation cannot flow through the gas easily, and it backs up like water behind a dam. When enough heat builds up, the gas begins to churn as hot gas rises upward and cool gas sinks downward. This heat-driven circulation of a fluid is called convection, the third way energy can move inside a star. You are familiar with convection: The rising wisp of smoke above a candle flame is carried by convection. Energy is carried upward in these convection currents as rising hot gas (red in the right-hand diagram within Figure 11-13) and as sinking cool gas (blue in the right-hand diagram within Figure 11-13). Convection is important not only because it carries energy but also because it mixes the gas.

11-5 The Source of Stellar Energy

IN THE PREVIOUS SECTION YOU LEARNED that the sun and other stars are stable because their centers have very high temperature and, therefore, pressure. Stars are born when gravity pulls

interstellar matter together. When the density and temperature at the centers of the new stars become high enough, nuclear fusion begins making energy. This supplies the energy that keeps the core hot enough, with high enough pressure, so that the star remains stable. In this section, you will learn the details of how that happens.

A Review of the Proton–Proton Chain

In Chapter 8 you visited the center of the sun and discovered that it creates energy through hydrogen fusion in a series of nuclear reactions called the proton–proton chain (see Figure 8-9). That reaction begins with the fusion of two protons, which are hydrogen nuclei. Protons have positive charges and repel each other electrically. As you learned earlier, electrical force is also called the Coulomb force, so the resistance of protons to being combined is called the Coulomb barrier. High-speed collisions are required to penetrate the Coulomb barrier, and high speed for atoms and subatomic particles means high temperature. Consequently, the proton–proton chain cannot effectively occur if the gas temperature is lower than about 4 million Kelvin.

You also discovered that the gas must be dense if the proton–proton chain is to produce significant energy. The fusion of two protons is unlikely, even if they collide, so a huge number of collisions are necessary to produce a few fusion reactions. Furthermore, a single cycle through the proton–proton chain produces only a tiny amount of energy, so a vast number of fusion reactions are needed to supply enough energy to support a star. The higher the gas density for a given temperature, the larger will be the number of fusion reactions.

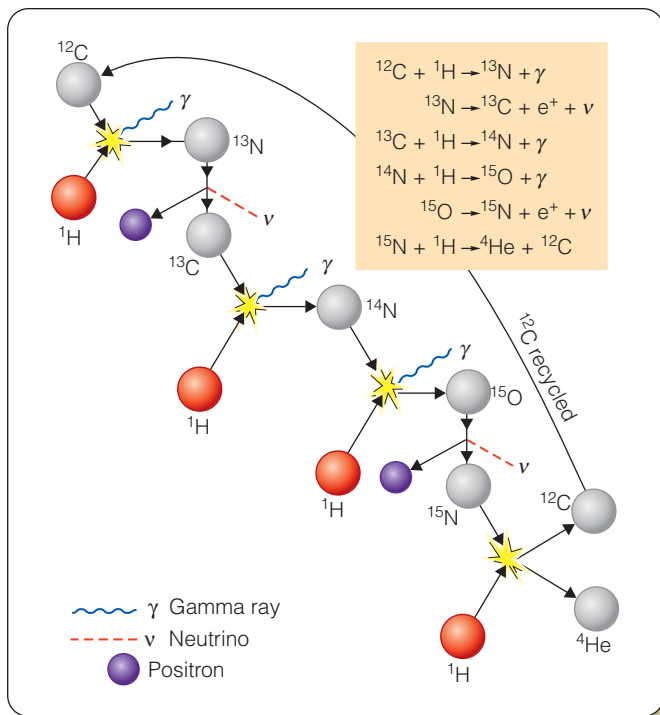
Those are the reasons why the proton–proton chain produces energy only near the sun’s center, where the temperature and density are high. In fact, only about the innermost 30 percent of the sun’s radius is hot enough to support fusion. The rest of the sun, farther from the center, isn’t hot and dense enough.

You might expect other stars to fuse hydrogen the same way the sun does, and you would be right for most stars. Some stars, however, can fuse hydrogen using a different recipe, and that makes a big difference to their structure and lifetimes.

The CNO Cycle

Main-sequence stars more massive than 1.1 solar masses are hot enough to fuse hydrogen into helium using the **CNO cycle**, a hydrogen fusion process that uses carbon, nitrogen, and oxygen as stepping-stones.

Look carefully at ■ Figure 11-14 and notice the steps in the CNO cycle. The cycle begins with a carbon-12 nucleus absorbing a proton and becoming nitrogen-13, which decays to become carbon-13. The carbon-13 nucleus absorbs a second proton and becomes nitrogen-14, which absorbs a third proton and becomes oxygen-15. The oxygen-15 decays to become nitrogen-15, which absorbs a fourth proton, ejects a helium



■ **Figure 11-14**

The CNO cycle uses ^{12}C as a catalyst to combine four hydrogen nuclei (^1H) to make one helium nucleus (^4He) plus energy. The carbon nucleus reappears at the end of the process, ready to start the cycle over.

nucleus, and becomes carbon-12. Notice that carbon-12 begins the cycle and ends the cycle, so the carbon-12 nucleus can be recycled over and over. Notice also that, along the way, four protons combine to make a helium nucleus. This CNO cycle has the same outcome as the proton–proton chain, but it is different in an important way.

The CNO cycle begins with a carbon nucleus combining with a proton, a hydrogen nucleus. Because a carbon nucleus has a positive charge six times higher than a proton, the Coulomb barrier is higher for this reaction than for the proton–proton chain. Temperatures higher than 16 million Kelvin are required so that significant numbers of protons are able to penetrate the Coulomb barrier of a carbon nucleus. In comparison, the proton–proton chain can make energy at temperatures as low as 4 million K. The CNO cycle therefore needs much hotter gas to operate than does the proton–proton chain. The temperature at the very center of the sun is estimated to be 15 million K, which is why the sun makes nearly all of its energy from the proton–proton chain and only a little from the CNO cycle.

The CNO cycle and the proton–proton chain both fuse hydrogen to make helium. The temperature sensitivity of the CNO cycle means that O and B stars, with the highest temperature cores,

create nearly all of their energy via the CNO cycle. As you have learned, O and B stars have very high luminosities and short lifetimes, making them prominent advertisements of star-forming regions.

Inside Stars

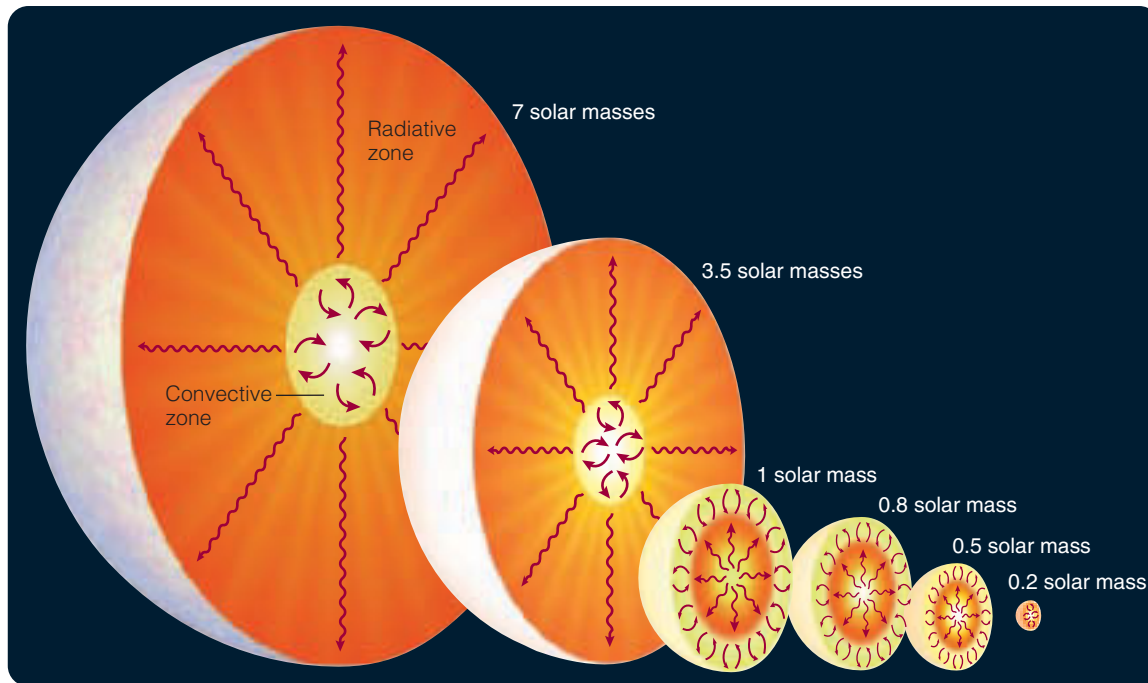
One important point for you to consider is that it is not correct to say “the sun’s core is hot because nuclear reactions occur there.” That statement reverses cause and effect. Rather, it is correct to say the sun and other stars have nuclear reactions in their cores because the temperature is hot enough there. You observe the sun to be stable; therefore, it must have a certain temperature, pressure, and density in its core. It would have about that same temperature in its core even if somehow you could magically turn off the nuclear reactions. But then, without a source of energy to replace the luminosity pouring out into space, the sun would gradually lose its internal energy and start slowly contracting again, as was true during its protostellar phase before the nuclear reactions started.

In Chapter 9, you discovered that the stars on the main sequence are ordered according to mass. Combining this with what you know about hydrogen fusion reveals that there are two kinds of main-sequence stars: (1) massive stars, on the upper main sequence, fuse hydrogen into helium via the CNO cycle, in which carbon, nitrogen, and oxygen nuclei act as catalysts but are not consumed; (2) low-mass stars, on the lower main sequence, including the sun, fuse hydrogen into helium via the proton–proton chain.

Viewed from the outside, those two types of stars differ only in size, temperature, and luminosity, but inside they are quite different. The upper-main-sequence stars are more massive and thus must have higher central temperatures to be able to stand against their own gravity. Those high central temperatures allow the star to fuse hydrogen on the CNO cycle, and that affects the internal structure of the star.

You have learned that the CNO cycle is extremely temperature sensitive. To illustrate, if the central temperature of the sun rose by 10 percent, energy production by the proton–proton chain would rise by about 46 percent, but energy production by the CNO cycle would shoot up 350 percent. This means that the more massive stars generate almost all of their energy in a tiny region at their very centers where the temperature is highest. A 10-solar-mass star, for instance, generates 50 percent of its energy in its central 2 percent of mass.

This concentration of energy production at the very center of the star causes a “traffic jam” as the energy tries to flow away from the center. Transport of energy by radiation can’t drain away the energy fast enough, and the central core of the star churns in convection as hot gas rises upward and cooler gas sinks downward. Farther from the center, the traffic jam is less severe, and the energy can flow outward as radiation. This



■ **Figure 11-15**

Inside stars. The more massive stars have small convective cores and radiative envelopes. Lower-mass stars, including the sun, have radiative cores and convective envelopes. The lowest-mass stars are convective throughout. The “cores” of the stars where nuclear fusion occurs (not shown) are smaller portions of the interiors. (Illustration design by M. Seeds)

means that massive stars have convective cores at their centers and radiative envelopes extending from their cores to their surfaces (■ Figure 11-15).

Main-sequence stars with less than about 1.1 solar masses cannot get hot enough to fuse much hydrogen on the CNO cycle. They generate nearly all of their energy by the proton–proton chain, which is not as sensitive to temperature, and thus the energy generation occurs in a larger region in the star’s core. The sun, for example, generates 50 percent of its energy in a region that contains 11 percent of its mass. Because the energy generation is not concentrated at the very center of the star, no traffic jam develops, and the energy flows outward as radiation. Only near the surface, where the gas is cooler and therefore more opaque, does convection stir the gas. Consequently, the less massive stars on the main sequence, including the sun, have radiative cores and convective envelopes, the opposite of higher-mass stars.

The lowest-mass stars have a slightly different kind of structure. For stars less than about 0.4 solar mass, the gas is relatively cool compared to the inside of more massive stars, and the radiation cannot flow outward easily. As a result, the entire bulk of these low-mass stars is stirred by convection.

The stars in the evening sky look much the same, but you have discovered that they are a diverse group, both outside and inside. Different kinds of stars make their energy in different

ways and have different internal structures. Those structures are determined by the principle of balance. But, can a star “lose” its balance? How do stars maintain their stability?

11-6 The Pressure–Temperature Thermostat

NEWBORN STARS CONTRACT and heat up until nuclear fusion begins. The energy flowing outward from the core heats the layers of gas, raises the pressure, and stops the contraction. This leads to an interesting question: How does the star manage to make just enough energy to stop contracting but not to start expanding? The key is the relationship between pressure and temperature that acts like a thermostat to keep the star burning steadily.

Consider what would happen if the reactions begin to produce too much energy. Normally, the nuclear reactions generate just enough energy to balance the inward pull of gravity. If the star makes slightly too much energy, the extra energy flowing out of the star would force its layers to expand slightly, lowering the central temperature and density and slowing the nuclear

reactions until the star regained stability. Thus, a star has a built-in regulator that keeps its nuclear reactions from occurring too rapidly.

The same thermostat keeps the reactions from dying down. Suppose the nuclear reactions begin making too little energy. Then the star would contract slightly, increasing the central temperature and density, which would in turn increase the nuclear energy generation until the star regained stability.

The stability of a star depends on this relation between pressure and temperature. If an increase or decrease in temperature produces a corresponding change in pressure, the thermostat functions correctly, and the star is stable. You will discover in the next chapter how the thermostat accounts for the relationship between mass and luminosity of main-sequence stars. In Chapter 13, you will see what happens to a star when the thermostat breaks down completely and the nuclear fires rage unregulated.

SCIENTIFIC ARGUMENT

What would happen if the sun stopped generating energy?

Sometimes one of the best ways to test your understanding is to build an argument based on an altered situation. Stars are supported by the outward flow of energy generated by nuclear fusion in their interiors. That energy keeps each layer of the star just hot enough for the gas pressure to support the weight of the layers above. Each layer in the star must be in hydrostatic equilibrium; that is, the inward weight must be balanced by outward pressure. If the sun stopped making energy in its interior, nothing would happen at first, but over many thousands of years the loss of energy from its surface would reduce the sun's ability to withstand its own gravity, and it would begin to contract. You wouldn't notice much for 100,000 years or so, but eventually the sun would lose its battle with gravity.

Stars are elegant in their simplicity—nothing more than a cloud of gas held together by gravity and warmed from the inside by nuclear fusion. Now build a different argument. **How does the star manage to make exactly the right amount of energy to support its weight?**

What Are We? Myth-Makers and Explainers

On cold winter nights when the sky is clear and the stars are bright, Jack Frost paints icy lacework across your windowpane. That's a fairy tale, of course, but it is a graceful evocation of the origin of frost. We humans are explainers, and one way to explain the world around us is to create myths.

An ancient Aztec myth tells the story of the origin of the moon and stars. The stars, known as the Four Hundred Southerners, and

the moon, the goddess Coyolxauhqui, plotted to murder their unborn brother, the great war god Huitzilopochtli. Hearing their plotting, he leaped from the womb fully armed, hacked Coyolxauhqui into pieces, and chased the stars away. You can see the Four Hundred Southerners scattered across the sky, and each month you can see the moon chopped into pieces as it passes through its phases.

Stories like these explain the origins of things and can make our universe seem more understandable. Science is a natural extension of our need to explain the world. The stories have become sophisticated scientific theories and are tested over and over against reality, but we humans build those theories for the same reason people used to tell myths.

Study and Review

Summary

- ▶ Stars are born from the gas and dust of the interstellar medium.
- ▶ The existence of massive, hot stars, such as the prominent stars of Orion, that cannot live very long is strong evidence that stars have formed recently.
- ▶ The gravity of giant molecular clouds makes them contract, but that is resisted by thermal energy in the gas and by magnetic fields, rotation, and turbulence. In at least some cases, clouds are compressed by passing shock waves, also known as **shocks** (p. 212), and star formation is triggered. The birth of massive stars can produce shock waves that trigger further star formation.
- ▶ The cold gas of interstellar space heats up as it contracts because the atoms fall inward in **free-fall collapse** (p. 213) and pick up speed. In other words, the gas is converting gravitational energy into thermal energy. The thermal energy of the contracting cloud can leak out, allowing the rapid collapse to continue, as long as the material remains transparent to spectral **cooling lines** (p. 214).
- ▶ Collapsing clouds dense enough to be opaque slow their contraction and become **protostars** (p. 214). Protostars form deep inside dusty **cocoons** (p. 214) and are not directly visible at visual wavelengths until the cocoons dissipate.
- ▶ The visible Orion Nebula is only a small part of a much larger dusty molecular cloud. Ionization by ultraviolet photons from the hottest star is lighting up the nebula and making it glow brightly.
- ▶ Only one star in the Orion Nebula is hot enough to emit the ultraviolet photons that ionize the gas and make the nebula glow.
- ▶ Infrared observations reveal clear evidence of active star formation deeper in the molecular cloud just to the northwest of the Trapezium.
- ▶ Many stars visible in the Orion Nebula are surrounded by disks of gas and dust. Such disks do not last long and are clear evidence that the stars are very young.
- ▶ **Bok globules** (p. 216) are small dark nebulae, some of which may be contracting to form stars. **Star-formation pillars** (p. 218) are formed when hot gas rushes away from newborn stars and encounters denser blobs of gas and dust.
- ▶ Protostars become visible as they cross the **birth line** (p. 220) in the H-R diagram. **T Tauri** (p. 222) stars have just emerged from their cocoons and are located between the birth line and the main sequence in the H-R diagram. Stars that are nearing the main sequence stage are generally termed **Young Stellar Objects (YSOs)** (p. 220).
- ▶ Many, perhaps most, protostars form surrounded by dusty **protostellar disks** (p. 220), and jets of gas can be emitted as **bipolar flows** (p. 223) along the axis of the spinning disk. Where the jets push into the surrounding gas, they can form nebulae called **Herbig-Haro objects** (p. 223).
- ▶ **Associations**, including **T associations** and **OB associations** (p. 224), are groups of stars born together but not bound by their mutual gravity. The presence of these associations in an area is evidence of recent star formation.
- ▶ Protostars and YSOs produce **stellar winds** (p. 224) and **radiation pressure** (p. 224) that can blow their remaining disk and cocoon material away and affect neighboring protostars.
- ▶ The law of **hydrostatic equilibrium** (p. 225) says that the weight pressing down on a layer of gas in a star must be balanced by the pressure in the gas. That shows that the inner layers of stars must be hotter because they must support more weight.
- ▶ The law of **energy transport** (p. 225) states that energy must flow from the hot stellar core to the cooler surface by conduction, radiation, or convection. The **opacity** (p. 226) of a gas is its resistance to the flow of radiation. In regions where the opacity of the gas does not permit radiation to carry away enough energy, the gas can churn in convection. One reason convection is important in stellar evolution is that it can mix material between inner and outer parts of stars. Conduction is less efficient than radiation or convection except in a few rare types of stars with very high densities.
- ▶ Many stars make their energy the same way the sun does using the proton-proton chain, which only operates at temperatures above 4 million degrees K needed to overcome the Coulomb barrier of electrical repulsion between positively charged atomic nuclei. The **CNO cycle** (p. 226) is more efficient, but it requires a higher temperature than the proton-proton chain because of the larger repulsion by carbon, etc. nuclei. Both processes combine four hydrogen nuclei to make one helium nucleus plus energy.
- ▶ The CNO cycle is highly temperature sensitive, so stars more massive than 1.1 solar masses, being hotter inside, make energy via the CNO cycle. Less massive stars, including the sun, make energy via the proton-proton chain.
- ▶ The temperature sensitivity of the CNO cycle causes energy production in upper-main-sequence stars to occur in a very small region near the center, and the cores of the stars are convective zones. These stars are radiative in their outer layers.
- ▶ The proton-proton chain is not very sensitive to temperature, so the energy generation of lower-main-sequence stars, including the sun, is more widely spread through the star's core, and the deep interior is radiative. The outer layers of these stars are convective.
- ▶ The lowest-mass stars are so cool that their gases are relatively opaque and they are convective throughout.

Review Questions

1. What factors resist the contraction of a cloud of interstellar matter?
2. Explain the different ways a giant molecular cloud can be triggered to contract.
3. What evidence is there that: (a) star formation has occurred recently? (b) protostars really exist? (c) the Orion region is actively forming stars?
4. How does a contracting protostar convert gravitational energy into thermal energy?
5. How does the geometry of bipolar flows and Herbig-Haro objects support the hypothesis that protostars are surrounded by rotating disks?
6. Describe the principle of hydrostatic equilibrium as it relates to the internal structure of a star.
7. How does energy get from the core of a star, where it is generated, to the surface, where it is radiated into space?
8. How does the CNO cycle differ from the proton-proton chain? How is it similar?
9. How does the extreme temperature sensitivity of the CNO cycle affect the structure of stars?
10. How does the pressure-temperature thermostat control the nuclear reactions inside stars?
11. **How Do We Know?** How would you respond to someone's comment about star formation, "That's only a theory"?
12. **How Do We Know?** Why can't scientists prove a scientific theory is totally correct?

Discussion Questions

1. Ancient astronomers, philosophers, and poets assumed that the stars were eternal and unchanging. Is there any observation they could have made or any line of reasoning that could have led them to conclude that stars don't live forever?
2. How does hydrostatic equilibrium relate to hot-air ballooning?

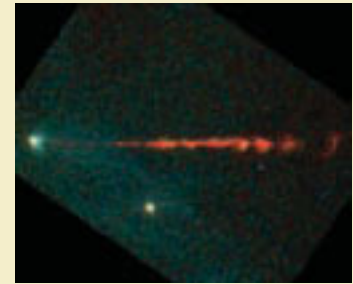
Problems

1. The expanding bubble of hot gas inflated by the cluster of new stars in its center, shown in Figure 11-3b, has a diameter of about 100 ly. If the bubble is 170,000 ly from Earth, what is the observed diameter of the bubble in arc seconds? (*Hint:* Use the small-angle formula, Chapter 3.)
2. If a giant molecular cloud is 50 pc in diameter and a shock wave can sweep through it in 2 million years, how fast is the shock wave going in kilometers per second?
3. If a giant molecular cloud has a mass of 10^{35} kg and it converts 1 percent of its mass into stars during a single encounter with a shock wave, how many stars can it make? Assume the stars each contain 1 solar mass.
4. If a protostellar disk is 200 AU in radius and the disk plus the forming star together contain 2 solar masses, what is the orbital speed at the outer edge of the disk in kilometers per second? (*Hint:* See Chapter 5.)
5. If a contracting protostar is five times the radius of the sun and has a temperature of only 2000 K, how luminous will it be? (*Hint:* See Chapter 9.)
6. The gas in a bipolar flow can travel as fast as 100 km/s. If the length of the jet is 1 ly, how long does it take for a blob of gas to travel from the protostar to the end of the jet?
7. If a T Tauri star is the same temperature as the sun but is ten times more luminous, what is its radius? (*Hint:* See Chapter 9.)

8. Circle all of the ^1H and ^4He nuclei in Figure 11-14 and explain how the CNO cycle can be summarized by $4\ ^1\text{H} \Rightarrow\ ^4\text{He} + \text{energy}$.
9. How much energy is produced when the CNO cycle converts 1 kg of mass into energy? Is your answer different if the mass is fused by the proton-proton chain?
10. If the Orion Nebula is 8 pc in diameter and has a density of about 600 hydrogen atoms/cm³, what is its total mass? (*Hint:* The volume of a sphere is $\frac{4}{3}\pi R^3$.)
11. The hottest star in the Orion Nebula has a surface temperature of 40,000 K. At what wavelength does it radiate the most energy? (*Hint:* See Chapter 7.)

Learning to Look

1. In Figure 11-7, a dark globule of dusty gas is located at top right. What do you think that globule would look like if you could see it from the other side?
2. Compare the nebula in Figure 11-3b with the image of the Orion Nebula on page 216. How are these two nebulae related?
3. Locate the star-formation pillars in Figure 11-6. What are they pointing at?
4. The star at right appears to be ejecting a jet of gas. What is happening to this star?





Visual wavelength image

Guidepost

Stars form from the interstellar medium and reach stability by fusing hydrogen in their cores. This chapter is about the long stable middle age of stars on the main sequence, and their old age as they swell to become giant stars. Here you will answer four essential questions:

— **Why is there a main sequence of stellar luminosities and surface temperatures?**

— **Why is there a simple relationship between the masses and luminosities of main-sequence stars?**

— **How does a star change as it exhausts its hydrogen?**

— **What evidence do astronomers have that stars really do evolve?**

This chapter is about how stars live. The next two chapters are about how stars die and the strange objects they leave behind.

Massive red supergiant star V838 Monocerotis is evolving rapidly. In early 2002, it flared up, and the expanding light is illuminating gas that was probably ejected in an earlier outburst. Spikes are produced by diffraction in the telescope. (NASA and The Hubble Heritage Team, AURA/STScI)

We should be unwise to trust scientific inference very far when it becomes divorced from opportunity for observational test.

— SIR ARTHUR EDDINGTON, *THE INTERNAL CONSTITUTION OF THE STARS*

EVERY STAR HAD A BEGINNING, and every star will someday have an ending, but in between the stars produce the light and energy that make our universe beautiful. The stars above you seem eternal, but their existence depends on the fusion of nuclear fuels in their cores; and, even as you look at them, they are using up their fuels and drawing closer to their ends.

In this chapter, you will see the full interplay of theory and evidence used to describe how stars change as they consume their nuclear fuels. As the quotation that opens this chapter warns, theory alone is never enough. At each step, astronomers must compare their theories with the evidence.

12-1 Main-Sequence Stars

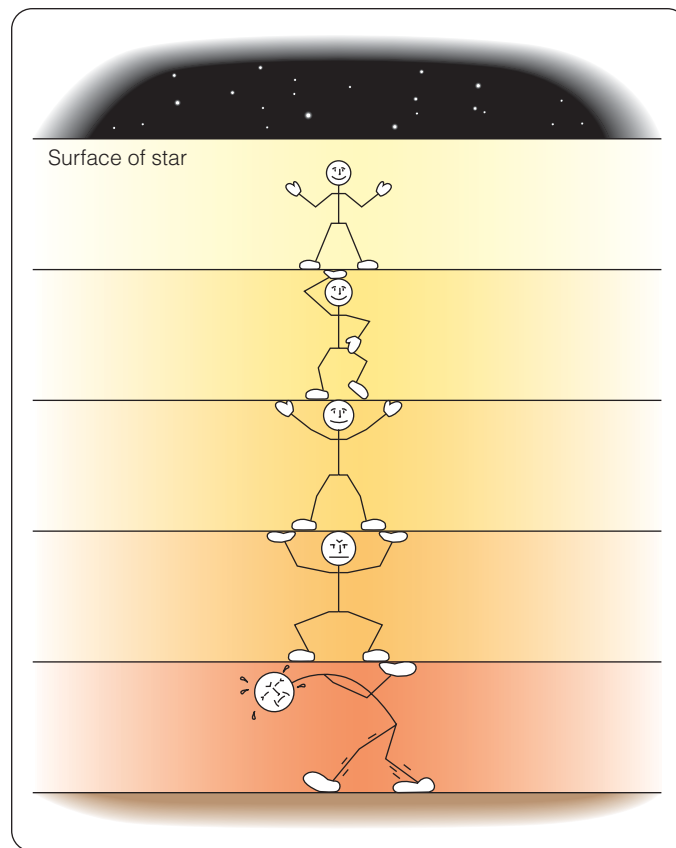
THE INSIDES OF STARS are forever beyond direct observation, so astronomers must use theories to describe how stars work. Nevertheless, astronomers test those theories at every opportunity against reality by making observations of real stars. That has produced one of the greatest triumphs of modern astronomy—the recognition that stars are not eternal and that mere humans can understand them.

Stellar Models

Astronomers can build mathematical models that describe the insides of stars, and the key to those models is balance. Every star is balanced between two forces, gravity that tries to make it contract and internal pressure that tries to make it expand. As you learned in Chapter 11, a star's internal layers are balanced in hydrostatic equilibrium. By defining the layers mathematically, astronomers can discuss the conditions at different levels inside the star—what they call the “structure” of the star (■ Figure 12-1).

The internal structure of a star can be described by four simple laws of physics, two of which you have already met in Chapter 11. In addition to the law of hydrostatic equilibrium, the law of energy transport describes how energy flows from hot to cool regions by radiation, convection, or conduction.

To these two laws you can add two basic laws of nature. The **conservation of mass law** says that the total mass of the star must equal the sum of the masses in its shells with the added requirement that the mass be smoothly distributed through the star. No gaps are allowed. The **conservation of energy law** says that the amount of energy flowing out the top of a shell in the



■ **Figure 12-1**

Structure in a star refers to the temperature, density, pressure, and so on, in each layer. Because each layer, like an acrobat in a circus stunt, must support the weight of everything above, astronomers can compute the conditions in each layer from the surface down to the center. Compare with Figure 11-12.

star must be equal to the amount of energy coming in at the bottom of the shell plus whatever energy is generated within the shell. This means that the energy leaving the surface of the star, its luminosity, must equal the sum of the energy generated in all of the shells inside the star. This is like saying that the total number of new cars driving out of a factory must equal the sum of cars manufactured on each assembly line. No car can vanish into nothing or appear from nothing. Energy in a star may not vanish without a trace or appear out of nowhere.

The four laws of stellar structure, described in general terms in ■ Table 12-1, can be written as mathematical equations. By solving those equations numerically using computer programs, astronomers can build a mathematical model of the inside of a star.

If you wanted to build a model of a star, you would have to divide the star into at least 100 concentric shells and then write down the four equations of stellar structure for each shell. You would then have 400 equations that would have a total of 400 unknowns, namely, the temperature, density, mass, and energy flow in each shell. Solving 400 equations simultaneously is not easy, and the first such solutions, calculated by hand before the

Table 12-1 | The Four Laws of Stellar Structure

- | | |
|----------------------------|--|
| 1. Hydrostatic equilibrium | The weight on each layer is balanced by the pressure in that layer. |
| 2. Energy transport | Energy moves from hot to cool by radiation, convection, or conduction. |
| 3. Conservation of mass | Total mass equals the sum of the shell masses. No gaps are allowed. |
| 4. Conservation of energy | Total luminosity equals the sum of the energies generated in each shell. |

invention of electronic computers, took months of work. Now a properly programmed computer can solve the equations for a simple model in a few seconds and print a table of numbers that represent the conditions in each shell of the star. Such a table is a **stellar model**.

The table shown in ■ Figure 12-2 shows a model of the sun containing only 10 layers, but it is based on a model with many more layers. The bottom line in the table, for radius equal to 0.00, represents the center of the sun, and the top line, for radius equal to 1.00, represents the surface. The other lines in the table show the temperature and density in each shell, the mass inside each shell, and the fraction of the sun's luminosity that is flowing outward through the shell. You can use such a model to understand many things about the sun. For example, the model shows that all of the sun's energy is generated near the center. No energy is generated in the outer layers.

Notice that stellar models are quantitative; that is, properties are assigned specific numerical values. Earlier in this book, you used models that were qualitative—the Babcock model of the sun's magnetic cycle, for instance. Both kinds of models are useful, but a quantitative model can reveal deeper insights into how nature works because it incorporates the precision of mathematics (**How Do We Know? 12-1**).

Stellar models let astronomers understand the inside of a star, and they can also look into a star's past and future. In fact, astronomers can use models like a time machine to follow the evolution of a star over billions of years. To look into a star's future, astronomers can use a stellar model to determine how fast the star uses its fuel in each of its shells. As the fuel is consumed, the chemical composition of the gas changes, the opacity changes, and the amount of energy generated declines. By calculating the rates of these changes, astronomers can predict what the star will be like a few million years in the future. They can then repeat the process over and over and, step by step, follow the evolution of the star as it ages.

Although this sounds simple, it is actually a highly challenging problem involving nuclear and atomic physics, thermodynamics, and sophisticated computational methods. Only since the 1950s have computers made the rapid calculation of stellar models possible, and many of the advances in astronomy since then have been heavily influenced by the use of such models to study the structure and evolution of stars. The summary of star formation in the previous chapter is based on thousands of stellar

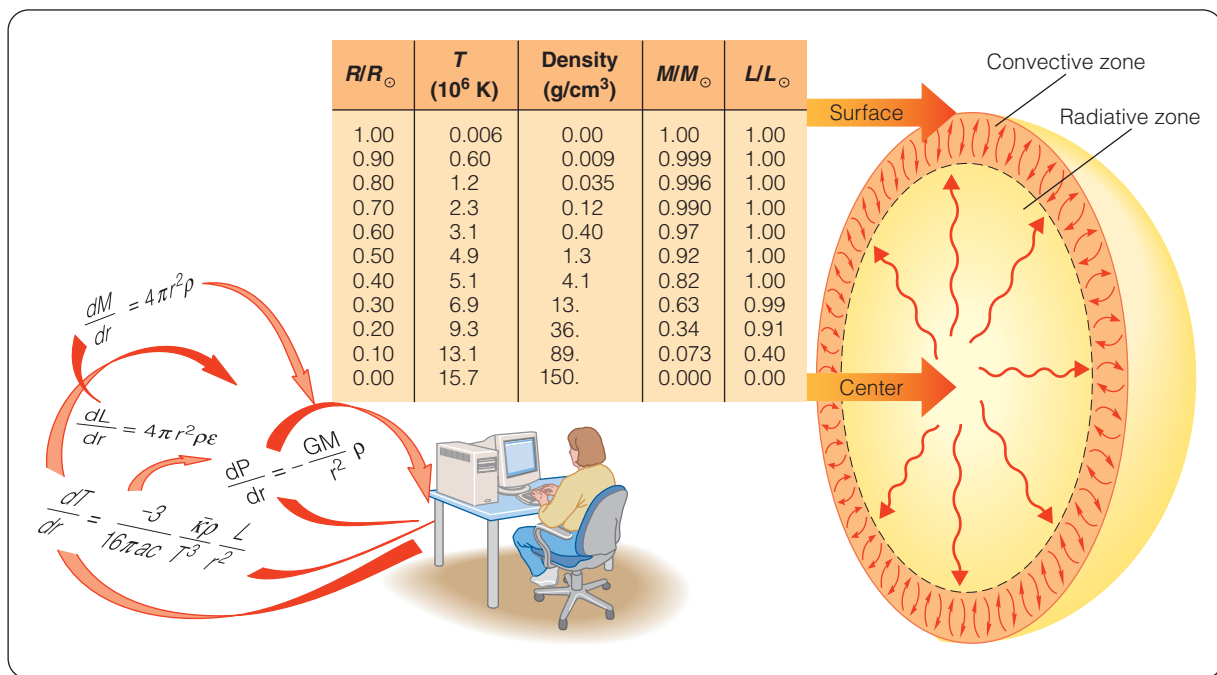


Figure 12-2

A stellar model is a table of numbers that represent conditions inside a star. Such tables can be computed using the four laws of stellar structure, shown here in mathematical form. The table in this figure describes the sun. (Illustration design by Mike Seeds.)

Mathematical Models

How can scientists study aspects of nature that cannot be observed directly? One of the most powerful methods in science is the mathematical model, a group of equations carefully designed to mimic the behavior of objects and processes that scientists want to study. Astronomers build mathematical models of stars to study the structure hidden deep inside them. Models can speed up the slow evolution of stars and slow down the rapid processes that generate energy. Stellar models are based on only four equations, but other models are much more complicated and may require many more equations.

For example, scientists and engineers designing a new airplane don't just cross their fingers, build it, and ask a test pilot to try it out. Long before any metal parts are made, mathematical models are created to test whether the wing design will generate enough lift, whether the fuselage can support the strain, and whether

the rudder and ailerons can safely control the plane during takeoff, flight, and landing. Those mathematical models are put through all kinds of tests: Can a pilot fly with one engine shut down? Can the pilot recover from sudden turbulence? Can the pilot land in a crosswind? By the time the test pilot rolls the plane down the runway for the first time, the mathematical models have flown many thousands of miles.

Scientific models are only as good as the assumptions that go into them and must be compared with the real world at every opportunity. If you are an engineer designing a new airplane, you can test your mathematical models by making measurements in a wind tunnel. Models of stars are much harder to test against reality, but they do predict some observable things. Stellar models predict the existence of a main sequence, the mass–luminosity relation, the observed numbers of giant and supergiant stars, and the shapes of H–R diagrams.



Before any new airplane flies, engineers build mathematical models to test its stability. (The Boeing Company)

Without mathematical models, astronomers would know little about the lives of the stars, and designing new airplanes would be a very dangerous business.

models. You will continue to rely on theoretical models as you study main-sequence stars in the next section and the deaths of stars in the next chapter.

Why Is There a Main Sequence?

Astronomers have confidence in their stellar models because the physics that goes into the models is well understood. Another reason for confidence is that the models are constantly checked against reality by comparing them with observations of real stars. With that confidence, astronomers can use the models to understand stars better. For example, the models explain why there is a main sequence.

Models of stars show that there is a main sequence because the centers of contracting protostars eventually grow hot enough to begin nuclear fusion. Deuterium, the heavy isotope of hydrogen, is the first nuclear fuel to fuse, but it is rare and produces little energy; stellar models show that it has no real effect on a contracting star. Hydrogen fusion is the big powerhouse; when it begins, it produces enough energy to stop the star's contraction. Stars reach equilibrium somewhere along the main sequence. Hot stars are more luminous, and cool stars are less luminous, as you would expect. There is, however, a question about the main sequence that you can now resolve by thinking about stellar models. Why does the luminosity of a star depend on its mass?

In Chapter 9, you used pairs of stars orbiting each other in binary systems to find the masses of stars and discovered that the masses of main-sequence stars are ordered along the main sequence. In other words, the least massive stars are at the bottom of the

H–R diagram, and the most massive stars are at the top. Further, you discovered a direct relationship between the mass of a star and its luminosity—the mass–luminosity relation. This is one of the most fundamental observations in astronomy, and stellar models can tell you why there must be a mass–luminosity relation.

The keys to understanding the mass–luminosity relation are the law of hydrostatic equilibrium, which says that pressure must balance weight, and the pressure–temperature thermostat, which regulates energy production. You have seen that a star's internal pressure stays high because the generation of thermonuclear energy keeps its interior hot. Because more massive stars have more weight pressing down on the inner layers, their interiors must have high pressures and thus must be hotter. For example, the temperature at the center of a 15-solar-mass star is about 34,000,000 K, more than twice the central temperature of the sun.

Because massive stars have hotter cores, their pressure–temperature thermostats are set higher. The nuclear fuel at the center of a 15-solar-mass star fuses over 3000 times more rapidly than the fuel at the center of the sun. The rapid reactions produce more energy, which flows outward toward the cooler surface, heating each level in the star and enabling it to support the weight pressing inward. When all that energy reaches the surface, it radiates into space and makes the star highly luminous. There is a mass–luminosity relation because each star must support its weight by generating nuclear energy, and more massive stars have more weight to support.

The main sequence is elegant in its simplicity, but it has more secrets to reveal. To understand the main-sequence stars even better, you should next look at its upper and lower ends.

The Upper End of the Main Sequence

Models of stellar structure give astronomers a way to think about the extreme ends of the main sequence, the most massive and least massive stars. The former are rare, but the latter are common. Nevertheless, both are very difficult to study.

Taken together, theory and observation predict that there is an upper limit to the mass of stars. First, astronomers don't find stars more massive than about 100 solar masses. Observations show that, as gas clouds contract, they can fragment to form two or more stars. The more mass a gas cloud contains, the more likely it is to fragment, so there aren't many extremely massive stars because most large gas clouds break into smaller fragments and form multiple-star systems.

Even if a very massive star does begin to form, stellar models reveal that the most massive stars (roughly 50 to 150 solar masses) are unstable. To support the tremendous weight in such stars, the internal gas must be very hot, and that means it must emit floods of radiation that flow outward through the star. The resulting radiation pressure blows gas away from the star's surface in powerful stellar winds. This mass loss from very massive stars could reduce a 60-solar-mass star to less than 30 solar masses in only a million years.

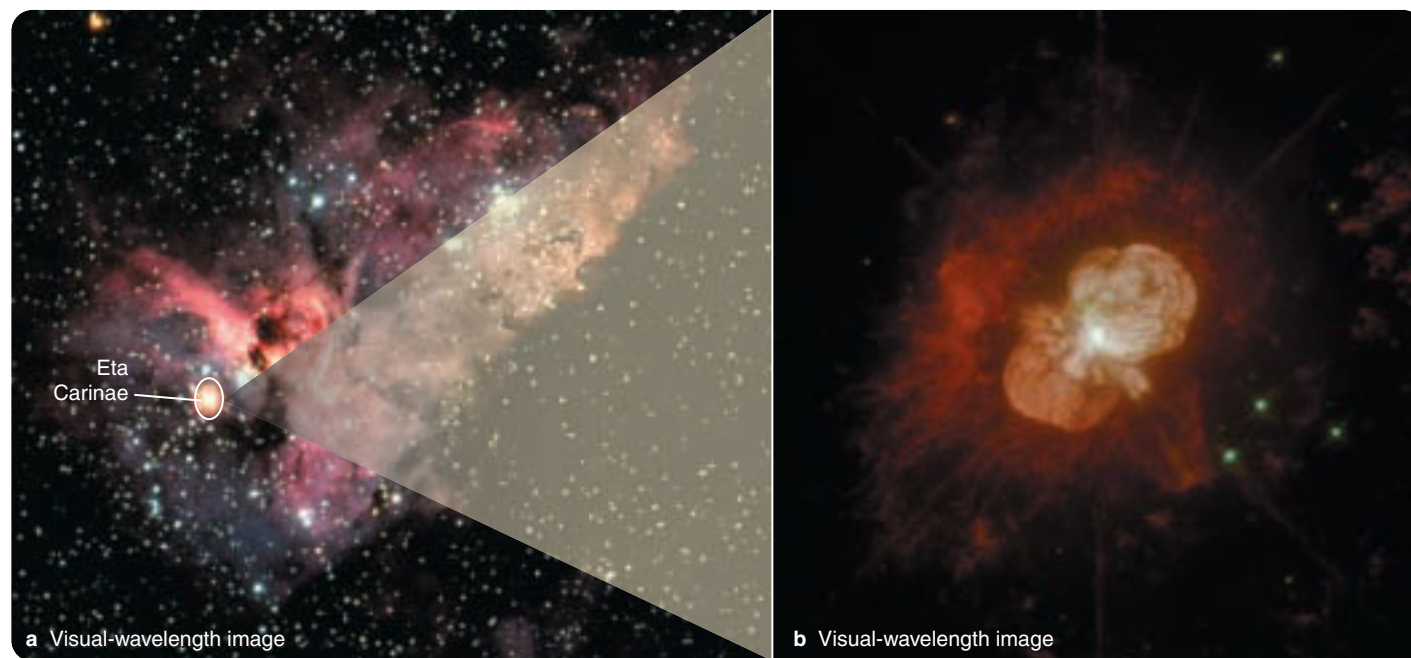
This process sets an upper limit on the masses of stars, but it is difficult to test the theory because it is hard to find truly massive stars. Most of the O and B stars in the sky have masses of 10 to 25 solar masses. The survey of stars at the end of Chapter 9

revealed that the stars at the upper end of the main sequence are very rare, so astronomers must search to great distances to find just a few. Nevertheless, a few stars are known that are thought to be very massive, and their spectra contain blueshifted emission lines. Kirchhoff's laws tell you that emission lines come from excited low-density gas, and the blueshift must be caused by a Doppler shift produced because the gas is coming toward Earth. These stars are losing mass.

■ Figure 12-3 shows a famous star, Eta Carinae. Observations suggest it is actually a binary containing two massive stars of 60 and 70 solar masses. The stars may have formed with about 100 solar masses each, but they are losing mass rapidly. An eruption in 1841 made Eta Carinae the second brightest star in the sky and ejected the two expanding lobes of dusty gas you can see in the picture. Although the star has faded, it is still very active, and more recent eruptions have ejected jets and an equatorial disk of gas and dust. Massive stars like Eta Carinae are clearly unstable.

The Lower End of the Main Sequence

The lower end of the main sequence is also difficult to study, not because the stars are rare but because they are dim. If a red dwarf from the lower end of the main sequence replaced the sun, it would shine only a few times brighter than the full moon. Such stars are very common, but they are difficult to find even when they are only a few light-years away.



■ **Figure 12-3**

(a) This star-formation nebula in the constellation Carina contains the massive star Eta Carinae. (NOAO/AURA/NSF) (b) Eta Carinae is actually two stars in a binary system, and they are so massive they are rapidly losing mass and inflating two lobes with a disk of ejected material between like a plate pressed between two basketballs. Each lobe is about half a light-year in diameter. Gas outside the lobes is high speed gas expelled in the outburst of 1841. (J. Hester/Arizona State Univ. NASA)

Stellar models predict that there are star-like objects even fainter than red dwarfs. Objects less massive than 0.08 solar mass cannot get hot enough in their cores to ignite hydrogen fusion. These **brown dwarfs** slowly contract, convert their gravitational energy into thermal energy, and radiate it away. A low-mass red dwarf containing 0.08 solar mass and fusing hydrogen has a surface temperature of about 2500 K, but brown dwarfs should have even lower temperatures, giving them a dull muddy-red color—thus the term “brown dwarf.” Brown dwarfs were difficult to find because they are so faint, but large surveys and infrared studies have turned up lots of them. Some are located in binary systems with normal stars (■ Figure 12-4), but large numbers are free-floating objects without stellar companions.

Brown dwarfs are clearly different from normal stars. Some brown dwarfs have methane bands in their spectra, and that means they must be quite cool. Methane molecules would be broken up at the temperatures of true stars. Color variations suggest that some brown dwarfs may be cool enough to have changing weather patterns.

The discovery of brown dwarfs has created a controversy. Are they failed stars, or are they planets? To discuss this, astronomers use a unit of mass related to Jupiter, the giant planet in our solar system. Jupiter is 1000 times less massive than the sun, and astronomers refer to the mass of brown dwarfs in Jupiter masses. A contracting mass containing more than 80 Jupiter masses can get hot enough to fuse hydrogen and become a red dwarf star. Consequently, a brown dwarf must be less than about 80 Jupiter masses. Because they can't get hot enough to fuse hydrogen, brown dwarfs can't be true stars. But astronomers tend to think of a planet as a non-luminous body that orbits a star, so can a brown dwarf floating free in space be called a planet?

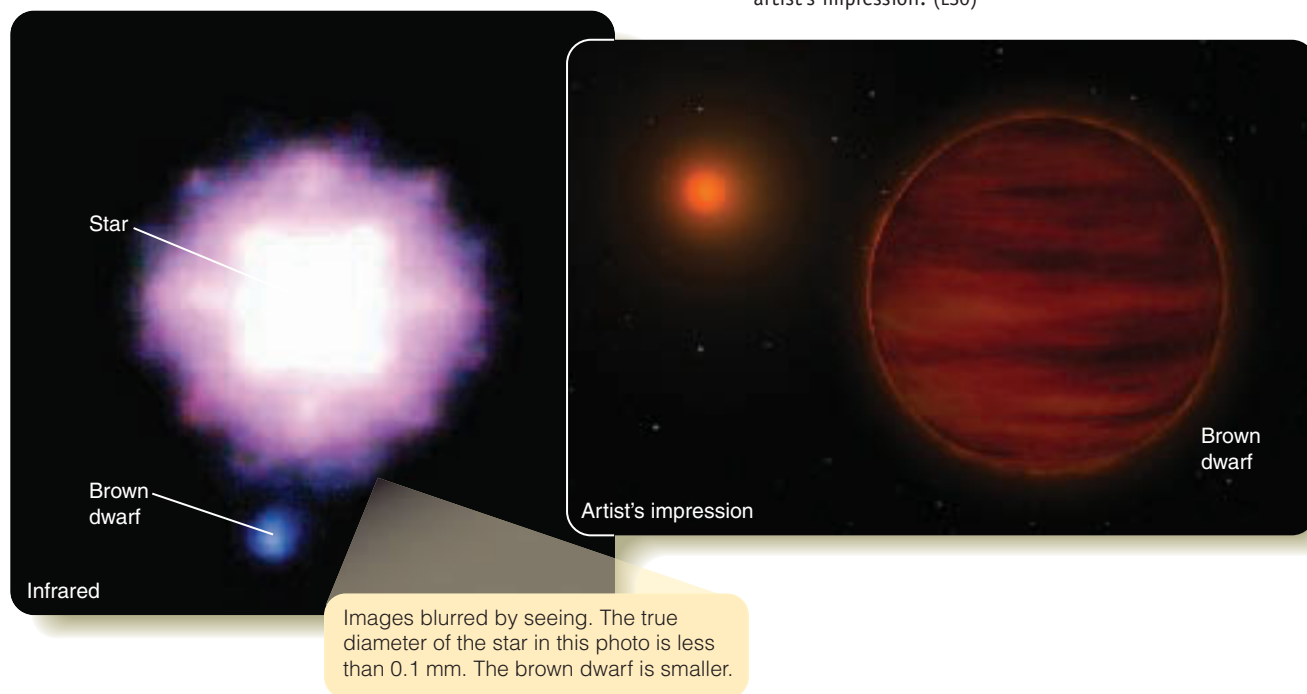
Brown dwarfs more massive than 13 Jupiter masses go through a phase during their formation when they can fuse deuterium, a heavy isotope of hydrogen, so some astronomers draw the line between brown dwarfs and planets at 13 Jupiter masses. By this definition, a brown dwarf would be an object with more than 13 and fewer than 80 Jupiter masses. However, deuterium fusion does not last very long, does not generate much energy, and does not stop the brown dwarf from cooling. Not everyone agrees that this is a good dividing line.

Another approach to the question of distinguishing brown dwarfs from planets is to consider how these objects form. A star forms from the contraction of a gas cloud, but astronomers know that planets form from the accumulation of solid bits of matter in disk-shaped nebulae around stars (a subject discussed in Chapter 19). In that case, free-floating brown dwarfs can't be planets. A problem with this definition is that it is difficult or impossible to tell how a mature low-mass object in a binary system originally formed, so if you use this definition, you won't necessarily know whether a given object should be called a brown dwarf or a planet.

The controversy over brown dwarfs is really an argument over the meaning of the words *star* and *planet* and doesn't really change astronomers' understanding. Brown dwarfs are the lowest mass objects at the bottom of the main sequence, and because they cannot sustain nuclear fusion, they must radiate away their thermal energy and slowly cool over billions of years.

■ Figure 12-4

Only 12.7 ly from the sun, a brown dwarf orbits a small star. Photographic effects give the brown dwarf a blue cast in the image, but if you could visit it, you would see an object slightly larger than the planet Jupiter glowing muddy red with a temperature just over 1000 K. Observations of brown dwarfs suggest that some have shifting weather patterns, as shown in the artist's impression. (ESO)



The Life of a Main-Sequence Star

A normal main-sequence star supports its weight by fusing hydrogen into helium, but its supply of hydrogen is limited. As it consumes hydrogen, the chemical composition in its core changes, and the star evolves. Mathematical models of stars allow astronomers to follow that evolution.

Hydrogen fusion combines four nuclei into one. Consequently, as a main-sequence star consumes its hydrogen, the total number of nuclei in its interior decreases. Each newly made helium nucleus exerts the same pressure as one hydrogen nucleus; because the gas has fewer nuclei, its total pressure is less. This unbalances the gravity–pressure stability, and gravity squeezes the core of the star more tightly. As the core contracts, its temperature and density increase, and the nuclear reactions burn faster, releasing more energy and making the star more luminous. This additional energy flowing outward through the envelope forces the outer layers to expand and cool, making the star slightly larger, brighter, and cooler.

As a result of these gradual changes in main-sequence stars, the main sequence is not actually a sharp line across the H–R diagram but rather a band (■ Figure 12-5). When a star begins its stable life fusing hydrogen, it settles on the lower edge of this

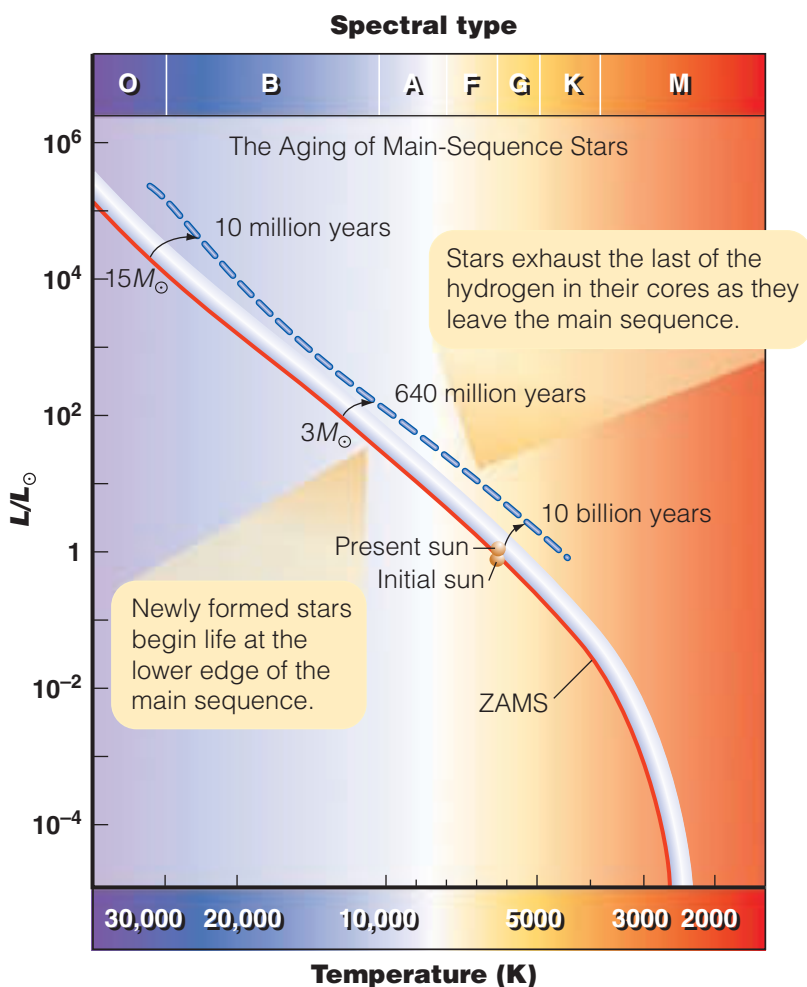
band, called the **zero-age main sequence (ZAMS)**. As it combines hydrogen nuclei to make helium nuclei, the point that represents the star’s luminosity and surface temperature moves upward and to the right, eventually reaching the upper edge of the main sequence just as the star exhausts nearly all of the hydrogen in its center. Astronomers find that main-sequence stars are plotted throughout this band depending on the stage of their main-sequence lives.

These gradual changes in the sun will spell trouble for Earth. When the sun began its main-sequence life about 5 billion years ago, it had only about 70 percent of its present luminosity. By the time the sun leaves the main sequence in another 5 billion years, it will have twice its present luminosity. By that time, the average temperature on Earth will have climbed by at least 55°C (about 100°F). As this happens over the next few billion years, the polar caps will melt, the oceans will evaporate, and much of the atmosphere will vanish into space. (This is not related to the current global warming, which affects Earth’s climate much more quickly and is not caused by the sun.) Clearly, the future of Earth as the home of life is limited by the evolution of the sun.

Once a star leaves the main sequence, it evolves rapidly and soon dies. The average star spends about 90 percent of its life fusing hydrogen on the main sequence. This explains why about 90 percent of all normal stars are main-sequence stars. You are most likely to see a star during its long, stable visit to the main sequence.

How long a star spends on the main sequence depends on its mass (■ Table 12-2). Massive stars have lots of fuel, but they use it rapidly and live short lives. Low-mass stars conserve their fuel and shine for billions of years. For example, a 25-solar-mass star will exhaust its hydrogen and die in only about 7 million years, whereas the sun can fuse hydrogen for about 10 billion years. This means, for one thing, that astronomers think that life is unlikely to develop on planets orbiting massive stars. These stars do not live long enough for life to get started and evolve into complex creatures. You will learn about this problem in detail in Chapter 26.

Red dwarfs have low masses and use their fuel so slowly they should survive for hundreds of billion years. Because the universe seems to be only about 14 billion years old, red dwarfs must still



■ **Figure 12-5**

Contracting protostars reach stability at the lower edge of the main sequence, the zero-age main sequence (ZAMS). As a star converts hydrogen in its core into helium, its position in the H–R diagram moves slowly across the main sequence, becoming slightly more luminous and slightly cooler. Once a star consumes all of the hydrogen in its core, it can no longer remain a stable main-sequence star. More massive stars age rapidly, but less-massive stars use up the hydrogen in their cores more slowly and live longer main-sequence lives.

■ **Table 12-2** | **Main-Sequence Stars**

Spectral Type	Mass (sun = 1)	Luminosity (sun = 1)	Approximate Years on Main Sequence
O5	40	405,000	1×10^6
B0	15	13,000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9

be in their infancy. None of them have exhausted their hydrogen fuel yet.

Vast numbers of faint, low-mass stars fill the sky. Look at page 187 and recall how much more common the lower-main-sequence stars are than the massive O and B stars. Main-sequence K and M stars are so faint they are difficult to locate, but they are very common. Nature makes more low-mass stars than massive stars, but that is not sufficient to explain the excess. An additional factor is the stellar lifetimes. Because low-mass stars not only form more often but also live long lives, there are many more of them in the sky than massive stars. The O and B stars are luminous and easy to locate; but, because of their fleeting lives, there are never more than a few on the main sequence at any one time.

The Life Expectancies of Stars

You have compared stellar lifetimes in a qualitative way; but, to really understand how stars evolve, you must be able to calculate how long they can survive. In fact, you can calculate the approximate life expectancy of a star from its mass.

Because main-sequence stars consume their fuel at an approximately constant rate, you can estimate the amount of time a star spends on the main sequence—its life expectancy, T —by dividing the amount of fuel by the rate of fuel consumption. You have made calculations like this before. If you drive a truck that carries 20 gallons of fuel and uses 2 gallons of fuel per hour, you know the truck can run for 10 hours.

The amount of fuel a star has is proportional to its mass, and the rate at which it burns its fuel is proportional to its luminosity; that means you could make a first estimate of the star's life expectancy by dividing mass by luminosity. Astronomers observe that 2-solar-mass main-sequence stars are about 11 times more luminous than the sun. Stars with 2 solar masses have 2 times as much fuel as the sun, but consume that fuel 11 times as quickly as the sun does, so they should live only

about 2/11, or 18 percent, as long as the sun. Notice that stars larger than the sun have shorter lifetimes because their fuel consumption rates are so much faster. You can make the calculation even easier if you remember from Chapter 9 that the mass–luminosity relation says that the luminosity of a main-sequence star is approximately proportional to $M^{3.5}$. The life expectancy then is:

$$T = \frac{M}{L} = \frac{M}{M^{3.5}} \text{ or } T = \frac{1}{M^{2.5}}$$

This means that you can estimate the life expectancy of a star by dividing 1 by the star's mass raised to the 2.5 power. If you express the mass in solar masses, the life expectancy will be in solar lifetimes.

For example, how long can a 4-solar-mass star live, relative to the sun?

$$T = \frac{1}{4^{2.5}} = \frac{1}{(4 \cdot 4 \cdot \sqrt{4})} = \frac{1}{32} \text{ solar lifetimes}$$

Detailed studies of models of the sun show that the sun, presently 5 billion years old, can last another 5 billion years. So, a solar lifetime is approximately 10 billion years, and a 4-solar-mass star will last about (10 billion)/32, or about 310 million, years.

This estimation of stellar life expectancies is very approximate. For example, the model ignores mass loss, which may affect the life expectancies especially of both very luminous and very faint stars. Nevertheless, it serves to illustrate an important point. Stars that are only slightly more massive than the sun have dramatically shorter lifetimes on the main sequence.

SCIENTIFIC ARGUMENT

Why is there a main sequence?

Some scientific arguments test a theory by comparing it to observations. You can begin with the simple fact that the weight of a star's material must be balanced by pressure, the principle of hydrostatic equilibrium. A contracting protostar is not quite in equilibrium, and gravity squeezes it tighter and tighter. As it contracts, its interior heats up; and, when it gets hot enough to fuse hydrogen into helium, the pressure–temperature thermostat takes over and regulates energy production so that the star makes just enough energy to support its own weight. That means that massive stars, having more weight to support, must have higher internal pressures and therefore must make more energy. Energy must flow from hot to cool, so that energy flows from the hot core of the star out to the cooler surface and is radiated into space. Massive stars, having more weight to support, must have their pressure temperature thermostats set higher, and that makes them more luminous. They reach stability with luminosities and surface temperatures that place them along the upper main sequence on the H–R diagram. Less massive stars support less weight and reach stability along the lower main sequence. There is a main sequence because stars in this stable life stage fuse hydrogen to support their own weight.

Now revise your argument. **Why do massive stars have such short life expectancies?**

12-2 Post-Main-Sequence Evolution

IN EARLIER CHAPTERS, you probably had questions about giant stars: Why are giant stars so large? Why do they have such low densities? And, why are they so uncommon? Now you are ready to answer those questions by learning about the evolution of stars after they leave the main sequence.

Expansion into a Giant

To understand how stars evolve, you must remember that they are not well mixed; that is, their interiors are not stirred. The centers of lower-mass stars like the sun are radiative, meaning the energy moves as radiation and not as circulating currents of heated gas. The gas does not move deep inside such stars, and that means they are not mixed at all. More massive stars have convective cores that mix the central regions (Figure 11-15), but these regions are not very large, and so, for the most part, these stars, too, are not mixed. (The lowest-mass stars are an exception that you will examine in the next chapter.)

In this respect, a star is like a campfire that is not stirred; the ashes accumulate at the center, and the fuel in the outer parts never gets used. Nuclear fusion consumes hydrogen nuclei and produces helium nuclei, the “ashes” that accumulate at the star’s center. Because nothing mixes the interior of the star, the helium nuclei remain where they are in the center, and the hydrogen in the star’s outer parts is not mixed down to the center where it could be fused.

The helium ashes that accumulate in the star’s core cannot fuse into heavier elements because the temperature is too low. As a result, the core eventually becomes an inert ball of helium. As this happens, the energy production in the core falls, and the weight of the outer layers forces the core to contract.

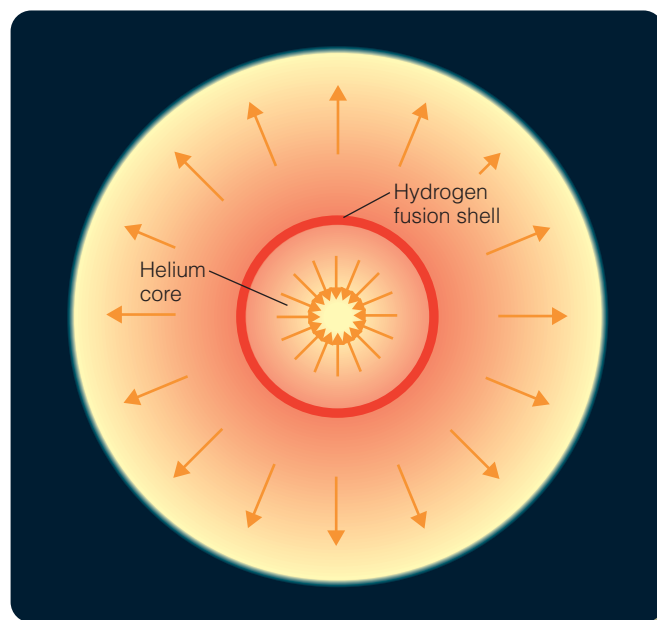
Although the contracting helium core cannot generate nuclear energy, it does grow hotter because it converts gravitational energy into thermal energy (see Chapter 11). The rising temperature heats the unprocessed hydrogen just outside the core, hydrogen that was never before hot enough to fuse. When the surrounding hydrogen becomes hot enough, it ignites in a thin, spherical shell. Like a grass fire moving outward from an exhausted campfire, the hydrogen-fusing shell slowly burns outward, leaving helium ash behind and increasing the mass of the helium core.

During this stage in its evolution, the star overproduces energy; that is, it produces more energy than it needs to balance its own gravity. The contracting helium core converts gravitational energy into thermal energy. Some of this energy heats the helium core, and some of that heat leaks outward through the star. At the same time, the hydrogen-fusion shell also produces energy as the contracting core brings fresh hydrogen closer to the center of the star and heats it to high temperature. The

result is a flood of energy flowing outward, forcing the outer layers of the star to puff up and expand the star into a giant (■ Figure 12-6).

The expansion of the envelope dramatically changes the star’s location in the H–R diagram. As the outer layers of gas expand, energy is absorbed in lifting and expanding the gas. The loss of that energy lowers the temperature of the gas. Consequently, the point that represents the star in the H–R diagram moves quickly to the right (in less than a million years for a star of 5 solar masses but in about 150 million years for a 1 solar mass star) (■ Figure 12-7). As the radius of a giant star continues to increase, the enlarging surface area makes the star more luminous, moving its point also upward in the H–R diagram. One of your Favorite Stars, Aldebaran, the glowing red eye of Taurus the bull, is a red giant, with a diameter 25 times that of the sun but with only half its surface temperature.

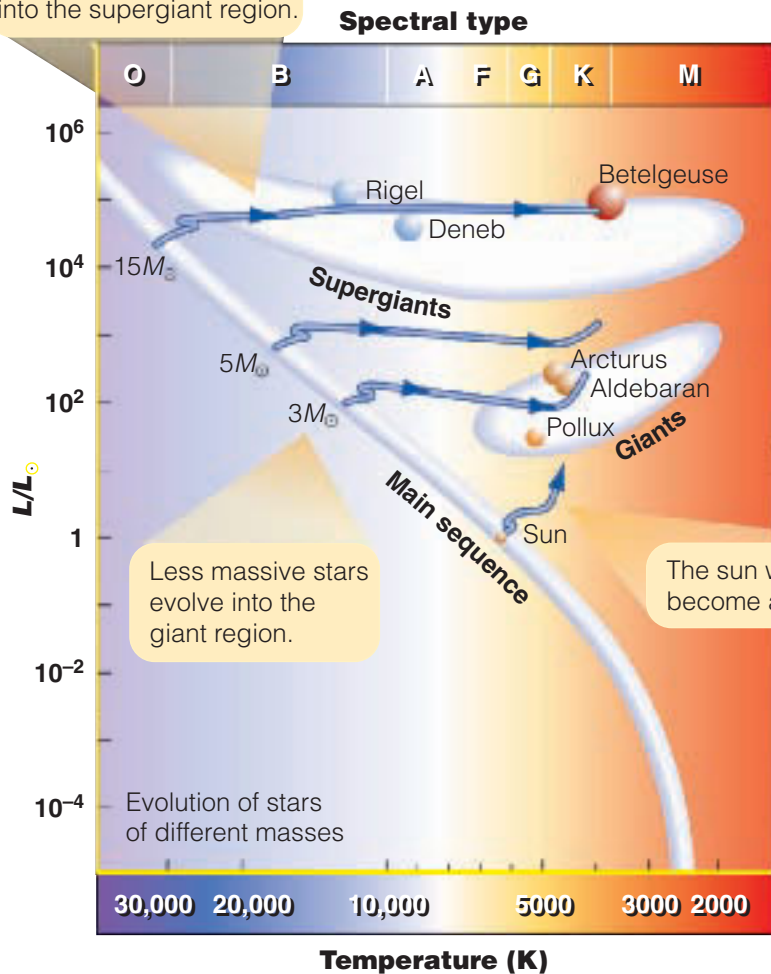
A medium-mass star like the sun evolves to become a giant, but more massive stars evolve across the upper H–R diagram and become supergiants, stars even larger than giants. Consider two more Favorite Stars. Betelgeuse (α Orionis) is a very cool, red supergiant over 800 times the diameter of the sun. Rigel (β Orionis) is a supergiant 50 times larger than the sun. It may seem odd to say that Rigel, a blue star, has expanded and cooled. At a temperature of 12,000 K, Rigel is hot and looks quite blue to your eyes. But when it was on the main sequence, Rigel had a much hotter surface. Even so, it would not have



■ **Figure 12-6**

When a star runs out of hydrogen at its center, it ignites a hydrogen-fusion shell. The helium core contracts and heats while the envelope expands and cools. (For a scale drawing, see Figure 12-9.)

Massive stars evolve from the main sequence into the supergiant region.



■ **Figure 12-7**

The evolution of a massive star moves the point that represents it in the H-R diagram to the right of the main sequence into the region of the supergiants such as Rigel and Betelgeuse. The evolution of a medium-mass star moves its point in the H-R diagram into the region of the giants such as those shown here.

looked much bluer because you cannot see the ultraviolet radiation that the hottest stars emit. Any star as hot or hotter than Rigel will look blue to your eyes, as shown in Figure 7-6. So, even though Rigel is blue, it is indeed a star that has expanded and cooled.

Now you can understand a few things you noticed in earlier chapters. Giants and supergiants are large because they have expanded, and they have very low densities for the same reason. Also, the giant and supergiant region of the H-R diagram contains a jumble of different mass stars because all main-sequence stars funnel through this part of the diagram as they die. (See Figure 9-23.)

Degenerate Matter

Although the hydrogen-fusion shell can force the envelope of the star to expand, it cannot stop the contraction of the helium core. Because the core is not hot enough to fuse helium, gravity squeezes it tighter, and it becomes very small. If you were to represent the helium core of a giant star with a baseball, the outer envelope of the star would be about the size of a baseball stadium. Yet the core would contain about 12 percent of the star's mass. When gas is compressed to such extreme densities, it begins to behave in surprising ways that can affect the evolution of a star.

Normally, the pressure in a gas depends on its temperature. The hotter a gas is, the faster its particles move, and the more pressure it exerts. The gas inside a star is ionized, so there are two kinds of particles, atomic nuclei and free electrons. Under normal conditions the gas in a star follows the same pressure-temperature laws as other gases, but if the gas is compressed to very high densities, as in the core of a giant star, two laws of quantum mechanics come into play, and the difference between electrons and nuclei becomes important.

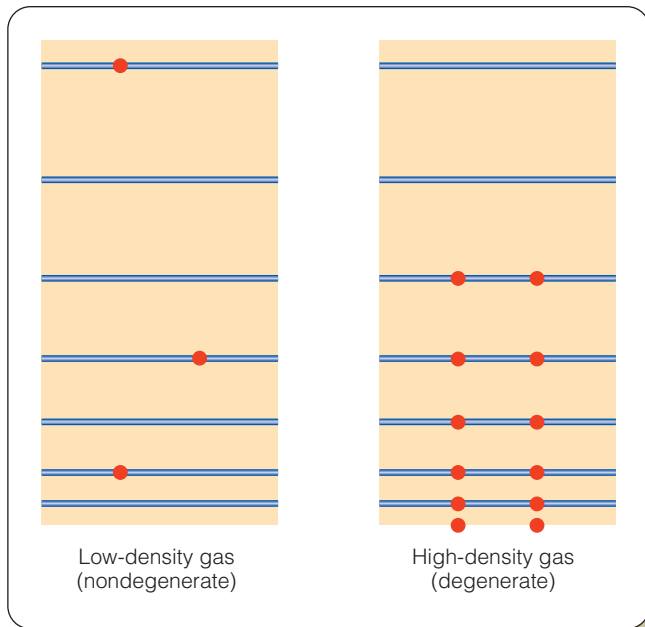
First, quantum mechanics says that the moving electrons confined in the star's core can have only certain amounts of energy, just as the electron in an atom can occupy only certain energy levels (see Chapter 7). You can

think of these permitted energies as the rungs of a ladder. An electron can occupy any rung but not the spaces between.

The second quantum mechanical law (called the Pauli exclusion principle) says that two identical electrons cannot occupy the same energy level. Because electrons spin in one direction or the other, two electrons can occupy a single energy level if they spin in opposite directions. That level is then completely filled, and a third electron cannot enter because, whichever way it spins, it will be identical to one or the other of the two electrons already in the level.

A low-density gas has few electrons per cubic centimeter, so there are plenty of energy levels available (■ Figure 12-8). If a gas becomes very dense, however, nearly all of the lower energy levels are occupied. In such a gas, a moving electron cannot slow down; slowing down would decrease its energy, and there are no open energy levels for it to drop down to. It can speed up only if it can absorb enough energy to leap to the top of the energy ladder, where there are empty energy levels.

When a gas is so dense that its electrons are not free to change their energy, astronomers call it **degenerate matter**.



■ **Figure 12-8**

Electron energy levels are arranged like rungs on a ladder. In a low-density gas, many levels are open, but in a degenerate gas, all lower-energy levels are filled.

Although it is a gas, it has two peculiar properties that can affect the star. First, the degenerate gas resists compression. To compress the gas, you must push against the moving electrons, and changing their motion means changing their energy. That requires tremendous effort because you must boost them to the top of the energy ladder. That is why degenerate matter, though still a gas, is harder to compress than the toughest hardened steel.

Second, the pressure of degenerate gas does not depend on temperature. To see why, note that the pressure depends on the speed of the electrons, which cannot be changed without tremendous effort. The temperature, however, depends on the motion of all the particles in the gas, both electrons and nuclei. If you add heat to the gas, most of that energy goes to speed up the motions of the nuclei, which move slowly and don't contribute much to the pressure. Only a few electrons can absorb enough energy to reach the empty energy levels at the top of the energy ladder. That means that changing the temperature of the gas has almost no effect on the pressure.

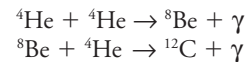
These two properties of degenerate matter become important when stars end their main-sequence lives. Eventually, many stars collapse into white dwarfs, and you will discover that these tiny stars are made of degenerate matter. But, long before that, the cores of some giant stars become so dense that they are degenerate, a situation that can produce a cosmic bomb.

Helium Fusion

Hydrogen fusion leaves behind helium ash, which cannot fuse at the relatively low temperatures of hydrogen fusion. Helium nuclei (two protons plus two neutrons) have a positive charge twice that of a hydrogen nucleus (a proton), which means the Coulomb barrier is higher. At the temperature of hydrogen fusion, helium nuclei move too slowly and collide too gently to fuse.

As the star becomes a giant star, fusing hydrogen in a shell, its inner core of helium ash contracts and grows hotter. It may even become degenerate. Finally, as the temperature approaches 100,000,000 K, helium nuclei begin to fuse together to make carbon. Because three helium nuclei are needed to make a carbon nucleus, and because a helium nucleus is called an alpha particle, astronomers often refer to helium fusion as the **triple alpha process**.

You can summarize the helium-fusing process in two steps:

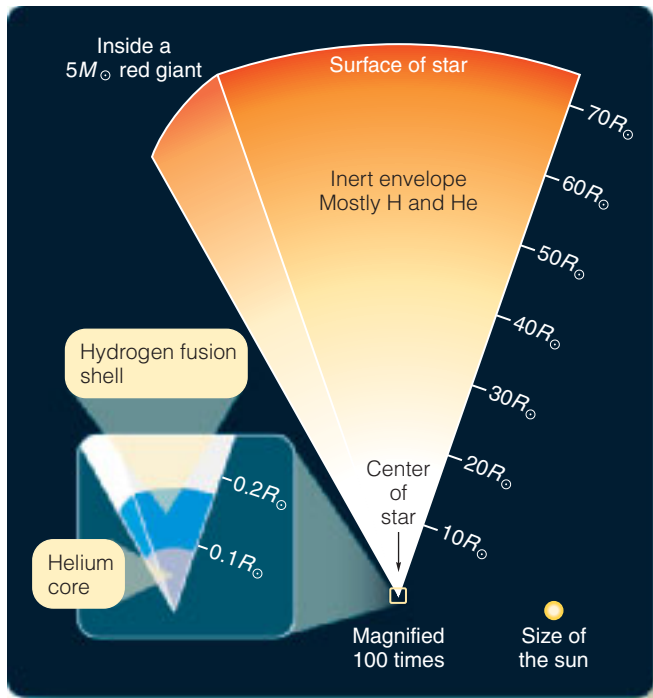


The first reaction actually absorbs a little bit of energy from the gas, but the second reaction produces almost 80 times more than the first reaction absorbs. This process is complicated by the fact that beryllium-8 is very unstable and may break apart, back into two helium nuclei, before it can absorb another helium nucleus. Three helium nuclei can also form carbon directly, but such a triple collision is unlikely.

Some stars begin helium fusion gradually, but stars in a certain mass range begin helium fusion with an explosion called the **helium flash**. This explosion occurs because the gas in the helium core becomes degenerate with a density that can reach 1,000,000 g/cm³. On Earth, a teaspoon of this material would weigh as much as a large truck. Because pressure no longer depends on temperature in a degenerate gas, the pressure–temperature thermostat that controls the nuclear fusion reactions no longer works.

When the helium ignites, it generates energy, which raises the temperature. But because the pressure–temperature thermostat is not working in the degenerate gas, the core does not respond to the higher temperature by expanding. Rather, the higher temperature forces the reactions to go faster, which makes more energy, which raises the temperature, which makes the reactions go faster, and so on. The ignition of helium fusion in a degenerate gas results in a runaway explosion so violent that for a few minutes the helium core generates 10¹⁴ times more energy per second than the sun. That's about 100 times the energy generated by all the stars in the Milky Way Galaxy.

Although the helium flash is sudden and powerful, it does not destroy the star. In fact, if you were observing a giant star as it experienced a helium flash, you would probably see no outward evidence of an eruption. The helium core is quite small



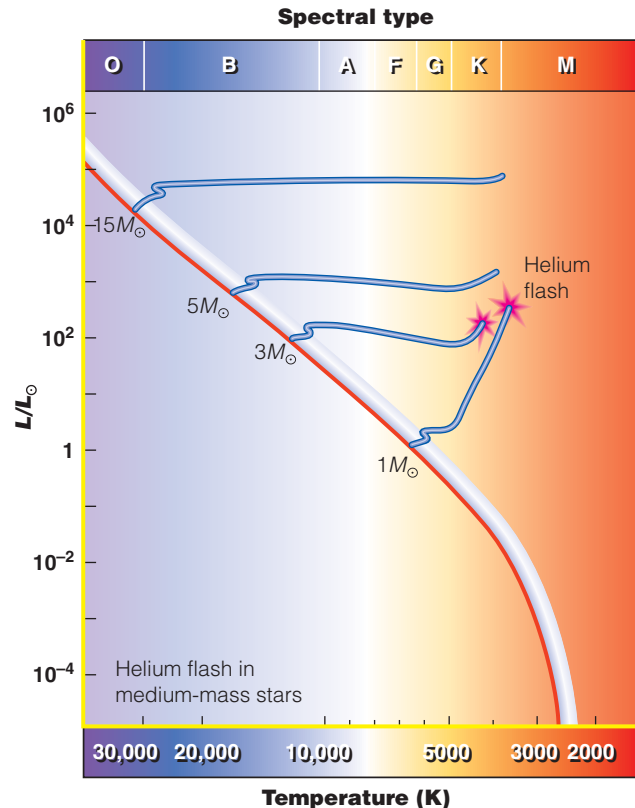
■ **Figure 12-9**

When a star runs out of hydrogen at its center, the core of helium contracts to a small size, becomes very hot, and begins nuclear fusion in a shell (blue). The outer layers of the star expand and cool. The red giant star shown here has an average density much lower than the air at Earth’s surface. Here M_{\odot} stands for the mass of the sun, and R_{\odot} stands for the radius of the sun. (Illustration design by Mike Seeds)

(■ Figure 12-9), and all of the energy of the explosion is absorbed by the distended envelope. Also, the helium flash is a very short-lived event. In a matter of minutes, the core of the star becomes so hot it is no longer degenerate, the pressure–temperature thermostat brings the helium fusion under control, and the star proceeds to fuse helium steadily in its core. You will learn about this post-helium-flash evolution later.

Astronomers calculating models of stellar evolution find that the sun and other medium-mass main-sequence stars will eventually undergo a helium flash, but not all stars do. Stars less massive than about 0.4 solar mass never get hot enough to ignite helium, and stars more massive than about 3 solar masses ignite helium before their cores become degenerate (■ Figure 12-10). In such stars, pressure always depends on temperature, so the pressure–temperature thermostat keeps the helium fusion under control.

If the helium flash occurs only in some stars and is a very short-lived event that is hardly visible from outside the star, why is it important? The answer is that it limits the reliability of the mathematical models astronomers use to study stellar evolution. Massive stars are not very common, and low-mass stars evolve so slowly that it is hard to find evidence of low-mass stellar evolution. For those reasons, studies of stellar evolution largely depend



■ **Figure 12-10**

Stars like the sun suffer a helium flash, but more massive stars begin helium fusion without a helium flash. Stars less than 0.4 times the mass of the sun cannot get hot enough to ignite helium. The zero-age main sequence is shown here in red at the lower edge of the main sequence.

on medium-mass stars, which do experience the helium flash. But the helium flash occurs so rapidly and so violently that computer programs cannot follow the changes in a star’s internal structure in detail. To follow the evolution of medium-mass stars like the sun past the helium flash, astronomers must make assumptions about the way the helium flash affects stars’ internal structures.

There is another reason why you should think about the helium flash. By seeing what happens when the pressure–temperature thermostat is turned off, you can appreciate its importance in maintaining the stability of stars. In the next chapter you will meet stars that explode violently because nuclear fusion becomes unregulated.

Post-helium-flash evolution is generally understood, and you can trace the stages in the following discussion in ■ Figure 12-11. After the gas ceases to be degenerate, helium fusion proceeds under the control of the pressure–temperature thermostat. Throughout these events, the hydrogen fusion shell continues to produce energy, but the new helium fusion energy produced in the core makes the core expand. That expansion absorbs energy previously used to support the outer layers of the star. As a result,

the outer layers contract, and the surface of the star grows slightly hotter. In the H–R diagram, the point that represents the star initially moves down toward lower luminosity and then to the left toward higher temperature. Later, as the star stabilizes fusing helium in its core, its luminosity recovers, but its surface grows hotter.

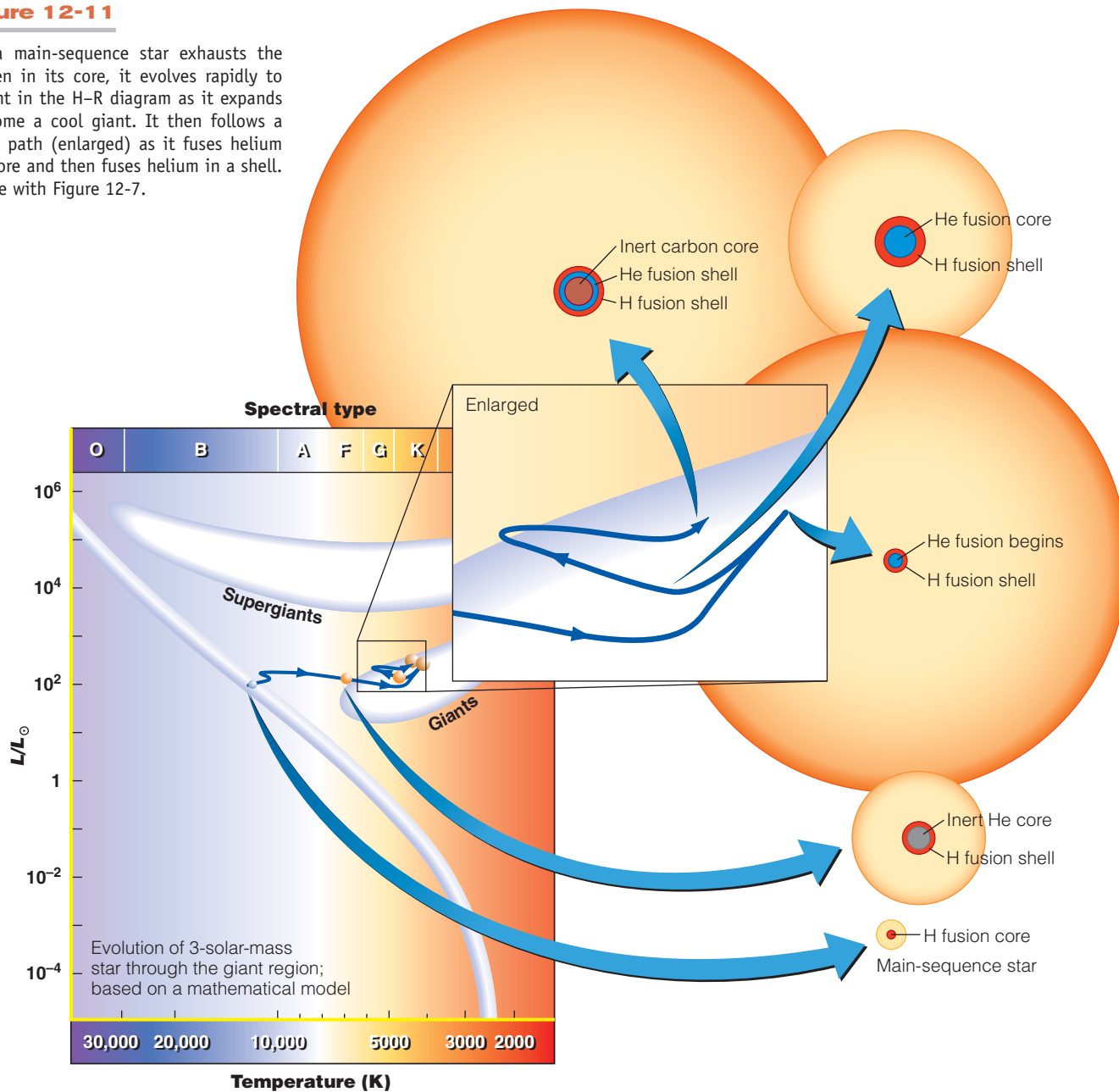
Helium fusion produces carbon, and some of the carbon nuclei absorb helium nuclei to form oxygen. A few of the oxygen nuclei absorb helium nuclei to form neon and then magnesium. Some of these reactions release neutrons, which, having no

charge, are more easily absorbed by nuclei to gradually build even heavier nuclei. These reactions are not important as energy producers. They are slow-cooker processes that form small traces of heavier elements right up to beryllium, nearly four times heavier than iron.

The nuclear “ashes,” mostly carbon and oxygen, accumulate at the center of a medium-mass star where they cannot fuse rapidly to make energy because the core is not hot enough. As the ashes accumulate, the core contracts, grows hotter, and ignites a helium fusion shell. At this stage, the star has two shells

■ **Figure 12-11**

When a main-sequence star exhausts the hydrogen in its core, it evolves rapidly to the right in the H–R diagram as it expands to become a cool giant. It then follows a looping path (enlarged) as it fuses helium in its core and then fuses helium in a shell. Compare with Figure 12-7.



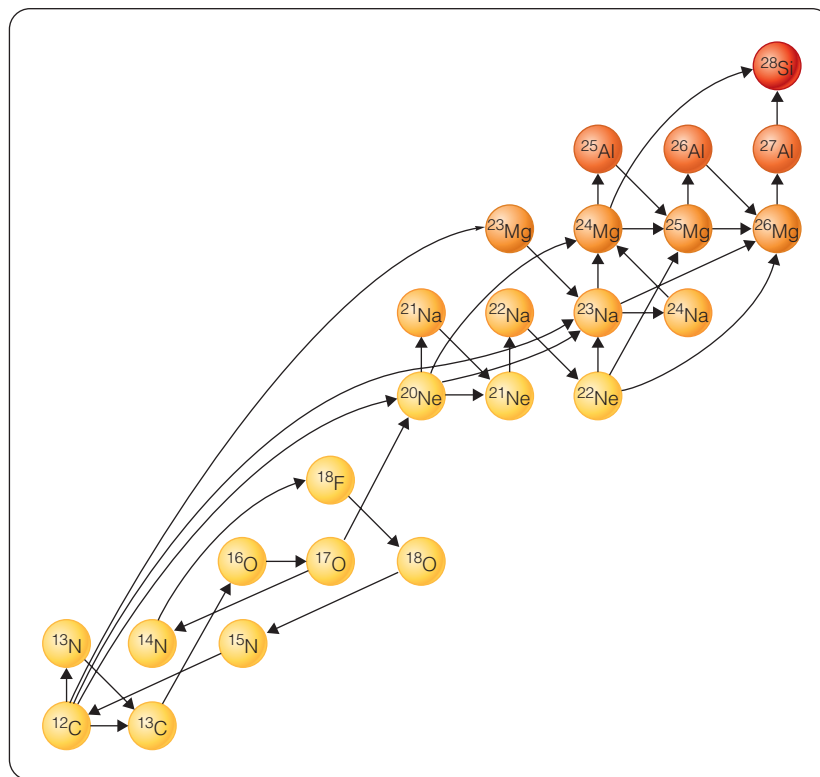
producing energy. A hydrogen fusion shell continues to move outward, leaving behind helium ash; a helium fusion shell moves outward into the helium, leaving behind carbon–oxygen ash. As the star’s carbon–oxygen core contracts, its outer layers expand, and its point in the H–R diagram moves back toward the right, completing a loop, as you can see in Figure 12-11.

Fusing Elements Heavier Than Helium

Understanding the evolution of stars after helium exhaustion requires great sophistication in computer models. As usual, what happens depends on the mass of the star. The inert core of carbon–oxygen ash contracts and becomes hotter, but only in stars more massive than about 4 solar masses can the core reach temperatures as high as 600,000,000 K, hot enough to fuse carbon. Subsequently, these stars can fuse neon, oxygen, silicon, and other heavy elements.

Carbon fusion in a star begins a complex network of reactions illustrated in Figure 12-12, where each circle represents a possible nucleus and each arrow represents a different nuclear reaction. Unstable nuclei can decay by ejecting an electron, ejecting a positron, ejecting a helium nucleus, or splitting into fragments.

As you can tell from all the arrows in Figure 12-12, the fusion of elements heavier than helium is not simple. Astronomers who model the structure and evolution of massive stars must use sophisticated nuclear physics to compute the amount of energy produced and to follow the changes in chemical composition that occur as the stars fuse carbon and heavier elements. Stars in this stage of their evolution develop complex internal structure as they fuse one heavy element after another in concentric shells. Like great spherical cakes with many layers, the stars can fuse a number of different elements simultaneously in different shells.



■ **Figure 12-12**

Carbon fusion involves many possible reactions that build numerous heavy nuclei.

Eventually, all stars face collapse. Less massive stars cannot get hot enough to ignite the heavier nuclei. The more massive stars that can ignite heavy nuclei consume their fuels at a tremendous rate, so they run through their available fuel quickly (Table 12-3). No matter what the star’s mass, it will eventually run out of usable fuels, and gravity will win the struggle with pressure. You will explore the ultimate deaths of stars in the next chapter.

The time a star spends as a giant or supergiant is small compared with its life on the main sequence. The sun, for example, will spend about 10 billion years as a main-sequence star but only about a billion years as a giant. The more massive stars pass

■ **Table 12-3** | **Nuclear Reactions in Massive Stars**

Nuclear Fuel	Nuclear Products	Minimum Ignition Temperature	Main-Sequence Mass Needed to Ignite Fusion	Duration of Fusion in a 25- M_{\odot} Star
H	He	4×10^6 K	$0.1 M_{\odot}$	7×10^6 yr
He	C, O	120×10^6 K	$0.4 M_{\odot}$	0.5×10^6 yr
C	Ne, Na, Mg, O	0.6×10^9 K	$4 M_{\odot}$	600 yr
Ne	O, Mg	1.2×10^9 K	$\sim 8 M_{\odot}$	1 yr
O	Si, S, P	1.5×10^9 K	$\sim 8 M_{\odot}$	~ 0.5 yr
Si	Ni to Fe	2.7×10^9 K	$\sim 8 M_{\odot}$	~ 1 day

through the giant stage even more rapidly. Because of the short time stars spend as giants, you will see relatively few giants. This illustrates an important principle in astronomy: The shorter the time a given evolutionary stage takes, the less likely you are to see stars in that particular stage. That explains why you see a great many main-sequence stars but few giants (see page 187).

12-3 Star Clusters: Evidence of Evolution

THE THEORY OF STELLAR EVOLUTION is so complex and involves so many assumptions that astronomers would have little confidence in it were it not for the evidence provided by clusters of stars. By observing and comparing the properties of star clusters of different ages, you can see clear evidence of the evolution of stars.

To grasp the difficulty of understanding stellar evolution, consider an analogy. Suppose a visitor to Earth who had never seen a tree wandered through a forest for an hour looking at mature trees, fallen seeds, young saplings, rotting logs, and rising sprouts. Could such an observer understand the life cycle of trees? Astronomers face the same problem when they try to understand the life story of the stars.

Humans do not live long enough to see stars evolve. You see only a momentary glimpse of the universe as it appears during your lifetime, a snapshot in which all the stages in the life cycle of the stars are represented. Unscrambling these stages and putting them in order is a difficult task. Only by looking at selected groups of stars—star clusters—can you see the pattern.

Observing Star Clusters

Plotting each star in a star cluster on an H–R diagram freezes a moment in the cluster’s history and makes the evolution of the stars visible. The stars in a cluster all formed at about the same time from the same cloud of gas, so they are all about the same age and have the same chemical composition. The differences you see among stars in a cluster must arise from differences in mass, and that is what makes stellar evolution visible. Study **Star Cluster H–R Diagrams** on pages 248–249 and notice three important points and four new terms:

- 1 There are two kinds of star clusters, *open clusters* and *globular clusters*. They look different, but their stars evolve in similar ways. You will learn more about these clusters in a later chapter.
- 2 You can estimate the age of a star cluster by observing the *turnoff point* in the distribution of the points that represent its stars in the H–R diagram.
- 3 Finally, notice that the shape of a star cluster’s H–R diagram is governed by the evolutionary path the stars take. The H–R diagrams of older clusters are especially clear in outlining how

stars evolve away from the main sequence to the giant region, then move left along the *horizontal branch* before evolving back into the giant region. By comparing clusters of different ages, you can visualize how stars evolve almost as if you were watching a film of a star cluster evolving over billions of years.

Were it not for star clusters, astronomers would have little confidence in the theories of stellar evolution. Star clusters make that evolution visible and assure astronomers that they really do understand how stars are born, live, and die.

The Evolution of Star Clusters

What you know about star formation and stellar evolution can help you understand star clusters and how they evolve.

A star cluster is formed when a cloud of gas contracts, fragments, and forms a group of stars. As you recall from Chapter 11, some groups of stars, called associations, are so widely scattered that the group is not held together by its own gravity. The stars in an association wander away from each other rather quickly. Some groups of stars are more compact; even after the stars become luminous and the gas and dust are blown away, gravity holds the group together as a star cluster.

Open clusters are not as old or as crowded as the globular clusters, and that helps explain their appearance. Close encounters between stars are rare in an open cluster where the stars are farther apart, and such clusters have an irregular appearance. The globular clusters appear to be nearly perfect globes because the stars are much closer together and encounters between stars are more common. The globular clusters have had time to evenly distribute the energy of motion among all of the stars so they have settled into a more uniform, spherical shape.

As a star cluster ages, some stars traveling a bit faster than others can escape. Globular clusters are compact and massive and have survived for 11 billion years or more. A star cluster with only a few widely distributed stars may evaporate completely as its stars escape one by one. Our sun may have formed in a star cluster 5 billion years ago, but there is no way to trace it back to its family home even if that star cluster still exists.

SCIENTIFIC ARGUMENT

Why is it only lower-mass stars that outline the horizontal branch?

This argument depends on timing. If a star cluster is young, it may contain a few massive stars, but because massive stars are so rare and evolve so rapidly you are unlikely to see more than a few of these stars evolving through the giant or supergiant regions of the H–R diagram. Lower-mass stars are very common and evolve slowly, so, in an older star cluster, you can see lots of stars in various stages of the post-main-sequence evolution. That outlines the horizontal branch.

Now construct a different argument. **What evidence can you cite that giant stars are main-sequence stars that have expanded to large diameters?**

12-4 Variable Stars: Evidence of Evolution

IT IS A **Common Misconception** that the stars are constant and unchanging. Stellar models show that stars slowly evolve as they consume their fuels, and the evidence from star clusters confirms these slow changes in structure. But is this enough evidence to be certain? One of the most important principles of science is that theories must be checked against all known evidence. Some stars that vary in brightness provide evidence of stellar evolution and illustrate once more the importance of energy flowing outward through the layers of the stars.

A **variable star** is any star that changes its brightness in a periodic way. Some variable stars are eclipsing binaries (see Chapter 9), but many others are single stars that grow brighter and fainter because of internal processes. These stars are often called **intrinsic variables** to distinguish them from eclipsing binaries. Of these intrinsic variables, two related kinds are centrally important to modern astronomy, even though the first star of that class was discovered centuries ago.

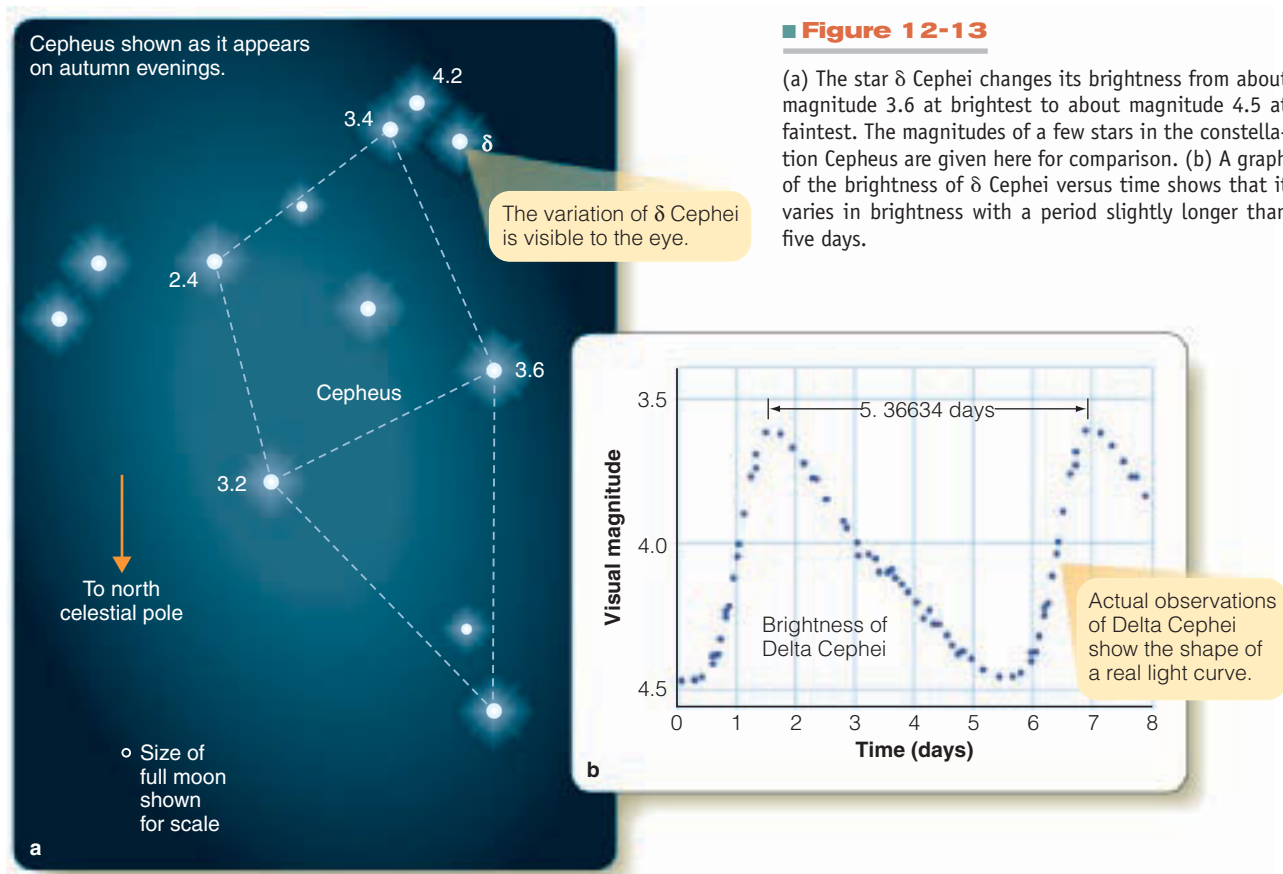
Cepheid and RR Lyrae Variable Stars

In 1784, the deaf and mute English astronomer John Goodricke, then 19 years old, discovered that the star δ Cephei is variable,

changing its brightness by almost a magnitude over a period of 5.37 days (■ Figure 12-13a). Goodricke died at the age of 21, but his discovery ensures his place in the history of astronomy. Since 1784, hundreds of stars like δ Cephei have been found, and they are now known as **Cepheid variable stars**.

Cepheid variables are supergiant or bright giant stars of spectral type F or G. The fastest complete a cycle—bright to faint to bright again—in about two days, whereas the slowest take as long as 60 days. A plot of a variable's magnitude versus time, known as a light curve, shows a typical rapid rise to maximum brightness and a slower decline (Figure 12-13b). Some Cepheids change their brightness by only 0.01 magnitude (about 1 percent), while others change by more than a magnitude. One of your Favorite Stars, Polaris, the North Star, is a Cepheid with a period of 3.9696 days and a very small amplitude. A related type of star, the **RR Lyrae variable stars**, are giant stars that are fainter than the Cepheids and pulsate with periods of less than a day.

Studies of Cepheids and RR Lyrae stars reveal two related facts of great importance. First, there is a **period–luminosity relation** that connects the period of pulsation of a Cepheid to its luminosity. The longer-period Cepheids are about 40,000 times more luminous than the sun, while the shortest-period Cepheids are only a few hundred times more luminous than the sun. Second, there are two types of Cepheids. Type I Cepheids,



Star Cluster H-R Diagrams

1 An **open cluster** is a collection of 10 to 1000 stars in a region about 25 pc in diameter. Some open clusters are quite small and some are large, but they all have an open, transparent appearance because the stars are not crowded together.

In a star cluster each star follows its orbit around the center of mass of the cluster.

AURA/NOAO/NSF

Visual-wavelength image

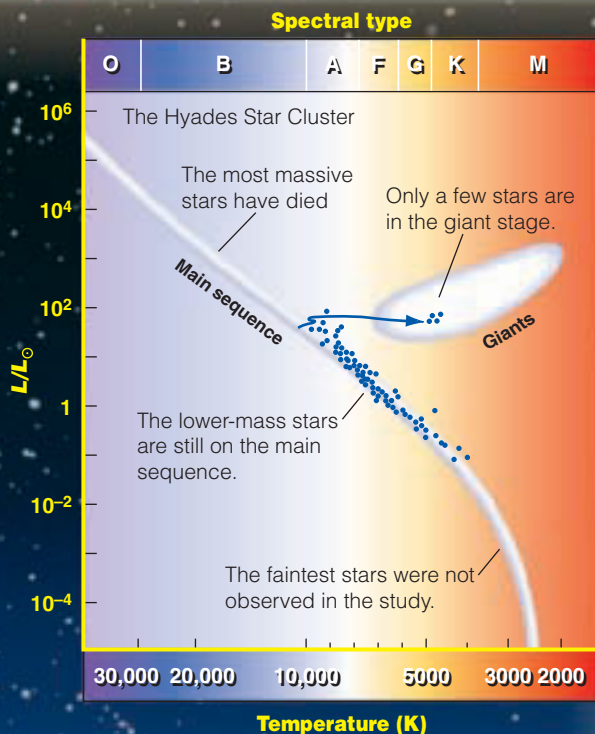
Open Cluster
The Jewel Box

1a A **globular cluster** can contain 10^5 to 10^6 stars in a region only 10 to 30 pc in diameter. The term “globular cluster” comes from the word “globe,” although globular cluster is pronounced like “glob of butter.” These clusters are nearly spherical, and the stars are much closer together than the stars in an open cluster.

Astronomers can construct an H-R diagram for a star cluster by plotting a point to represent the luminosity and temperature of each star.



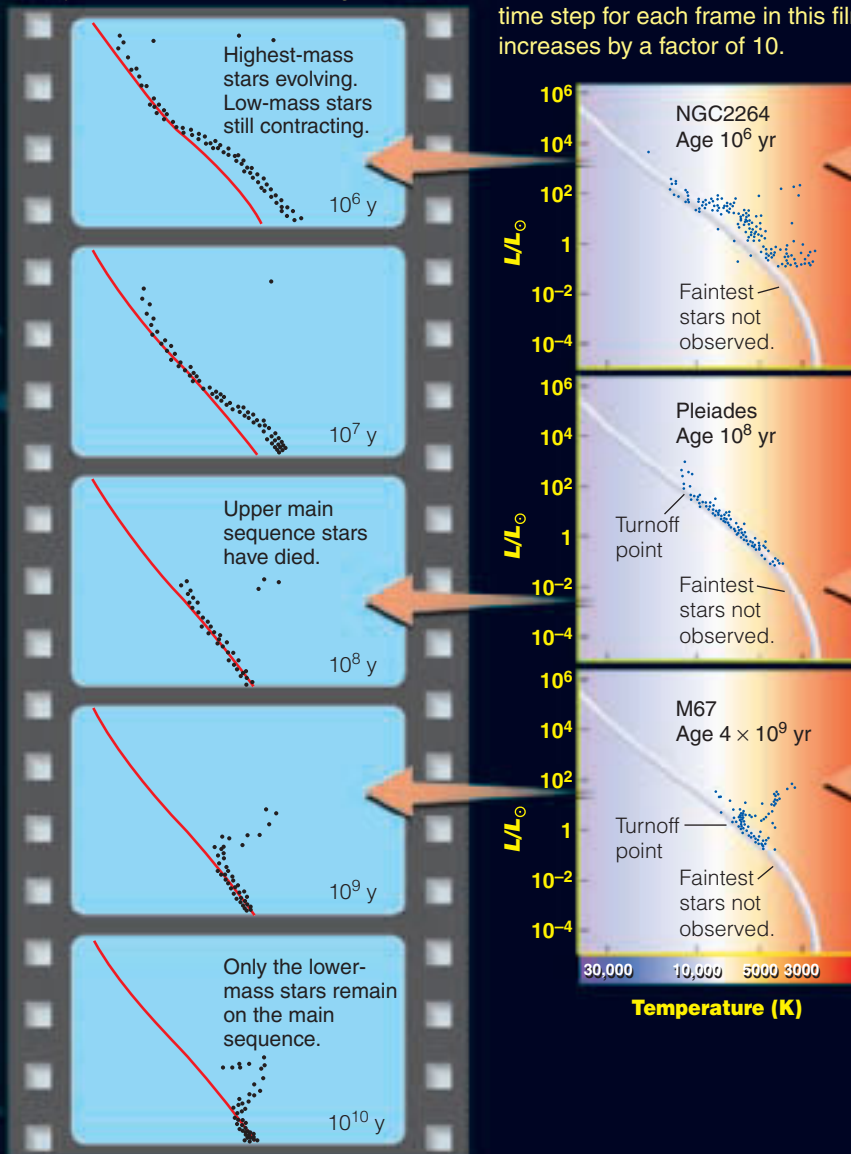
Visual-wavelength image



2 The H-R diagram of a star cluster can make the evolution of stars visible. The key is to remember that all of the stars in the star cluster have the same age but differ in mass. The H-R diagram of a star cluster provides a snapshot of the evolutionary state of the stars at the time you happen to be alive. The diagram here shows the 650-million-year-old star cluster called the Hyades. The upper main sequence is missing because the more massive stars have died, and our snapshot catches a few medium-mass stars leaving the main sequence to become giants.

As a star cluster ages, its main sequence grows shorter like a candle burning down. You can judge the age of a star cluster by looking at the **turnoff point**, the point on the main sequence where stars evolve to the right to become giants. Stars at the turnoff point have lived out their lives and are about to die. Consequently, the life expectancy of the stars at the turnoff point equals the age of the cluster.

3 From theoretical models of stars, you could construct a film to show how the H-R diagram of a star cluster changes as it ages. You can then compare theory (left) with observation (right) to understand how stars evolve. Note that the time step for each frame in this film increases by a factor of 10.



NGC 2264 is a very young cluster still embedded in the nebula from which it formed. Its lower-mass stars are still contracting, and it is rich in T Tauri stars.

Visual

Anglo-Australian Observatory / David Malin Images

The nebula around the Pleiades is produced by gas and dust through which the cluster is passing. Its original nebula dissipated long ago.

Visual

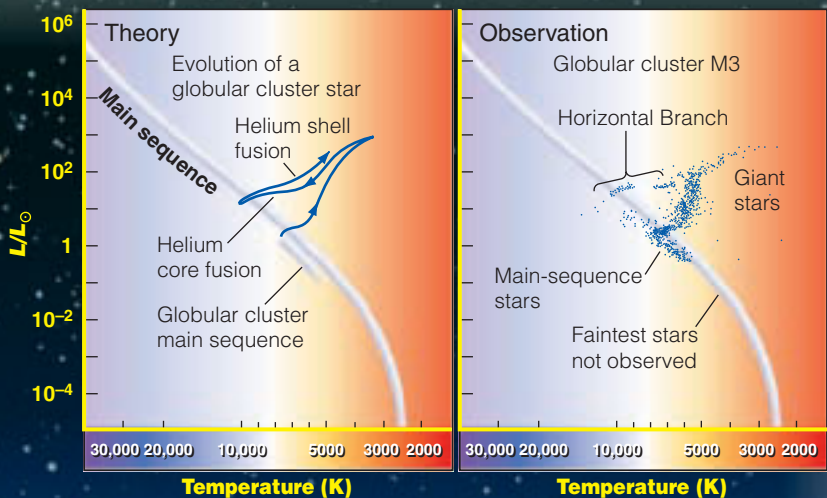
Caltech

M67 is an old open cluster. In photographs, such clusters have a uniform appearance because they lack hot, bright stars. Compare with the Jewel Box on the opposite page.

Visual

Nigel Sharp, Mark Hamma/AURA/NOAO/NSF

Globular cluster H-R diagrams resemble the last frame in the film, which tells you that globular clusters are very old.



3a The H-R diagrams of globular clusters have very faint turnoff points showing that they are very old clusters. The best analysis suggests these clusters are about 11 billion years old.

The **horizontal branch** stars are giants fusing helium in their cores and then in shells. The shape of the horizontal branch outlines the evolution of these stars.

The main-sequence stars in globular clusters are fainter and bluer than the zero-age main sequence. Spectra reveal that globular cluster stars are poor in elements heavier than helium, and that means their gases are less opaque. That means energy can flow outward more easily, which makes the stars slightly smaller and hotter. Again the shape of star cluster H-R diagrams illustrates principles of stellar evolution.

including δ Cephei itself, have chemical compositions like that of the sun, but type II Cepheids and the RR Lyrae stars are poor in elements heavier than helium. These facts are clues that will help you understand variable stars as evidence of stellar evolution.

Pulsating Stars

Why would a star pulsate? Why should there be a period–luminosity relation? Why are there two types of Cepheids? The answers to these questions will reveal some of the deepest secrets of the stars. To find the answers, you should start with the H–R diagram.

Remember that after a star leaves the main sequence, it fuses hydrogen in a shell, and the point that represents it in the H–R diagram moves to the right as the star becomes a cool giant. When it ignites helium in its core, the star contracts and grows hotter, and the point in the diagram moves to the left. Soon, however, the helium core is exhausted; helium fusion continues only in a shell, forcing the star to expand again; and the point in the H–R diagram moves back to the right, completing a loop. Because giant stars evolve through these stages, their sizes and temperatures change in complicated ways. Certain combinations of size and temperature make a star unstable, causing it to pulsate as an intrinsic variable star. In the H–R diagram, the region where size and temperature lead to pulsation is called the **instability strip**, as shown in the H–R diagram in ■ Figure 12-14.

What makes variable stars pulsate? Start with a stable star. You could make a stable star pulsate temporarily if you squeezed it and then released it. The star would rebound outward, and it might oscillate in and out for a few cycles, but the oscillation would eventually run down because of friction. The energy of the moving gas would be converted to heat and radiated away, and the star would return to stability with each layer of gas in hydrostatic equilibrium. To make a star pulsate continuously, some process must drive the oscillation, just as a spring in a windup clock is needed to keep it ticking.

Studies using stellar models show that variable stars in the instability strip pulsate like beating hearts because of an energy-absorbing layer in their outer envelopes. This layer is the region where helium is partially ionized. Above this layer, the temperature is too low to ionize helium, and below the layer it is hot enough to ionize all of the helium. Like a spring, the helium ionization zone can absorb energy when it is compressed and release it when the zone expands, and that is enough to keep the star pulsating.

You can follow this pulsation in your imagination. As the outer layers of a pulsating star expand, the ionization zone expands, and the ionized helium becomes less ionized and releases stored energy, which gives the expanding gas a little boost and the expansion goes a little faster. The surface of the star overshoots its equilibrium position—it expands too far—and eventually falls

back. As the surface layers contract, the ionization zone is compressed and becomes more ionized, which absorbs energy. Robbed of some of their energy, the layers of the star can't support the weight, and they compress a little faster. This allows the contraction to go even faster, and the in-falling layers overshoot the equilibrium point until the pressure inside the star slows them to a stop and makes them expand again.

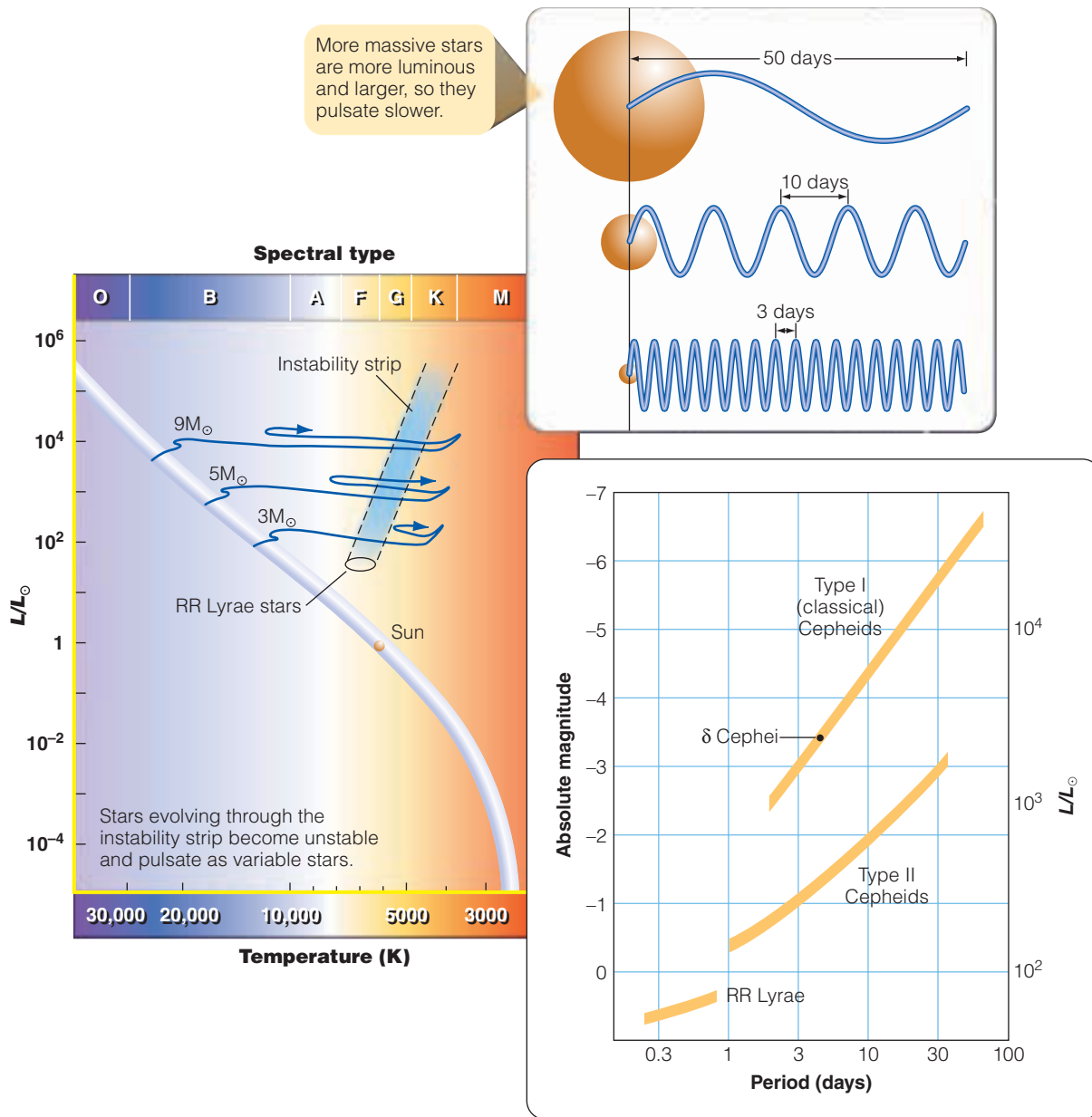
Cepheids change their radius by 5 to 10 percent as they pulsate, and this motion can be detected by observing Doppler shifts in their spectra. When the stars expand, the surface layers approach, and astronomers see a blueshift. When they contract, the surface layers recede, and astronomers see a redshift. Although a 10 percent change in radius seems like a large change, it affects only the outer layers of the star. The center of the star is much too dense to be affected.

Only stars in the instability strip have their helium ionization zone at the right depth to act as a spring and drive the pulsation. In cool stars, the zone is too deep and cannot overcome the weight of the layers above it. That is, the spring is overloaded and can't expand. In hot stars, the helium ionization zone lies near the surface, and there is little weight above it to compress it. That is, the spring never gets squeezed. The stars in the instability strip have the right combination of temperature and radius for the helium ionization zone to fall exactly where it is most effective, and that is why those stars pulsate.

Now you can also understand why there is a period–luminosity relation. The more massive stars are larger and more luminous. When they cross the instability strip, they cross higher in the H–R diagram. But the larger a star is, the more slowly it pulsates—just as when large bells vibrate. They go “bong” whereas little bells go “ding.” Pulsation period depends on size, which depends on mass, and mass also determines luminosity. So the most luminous Cepheids at the top of the instability strip are also the largest and pulsate most slowly. Less luminous Cepheids are smaller and pulsate faster. If you plot the average brightnesses of the variable stars against their periods of pulsation, you can clearly see the relationship between luminosity and period. Look at the right half of Figure 12-14 to see this relationship.

You know enough about stars to understand why there are two types of Cepheid variable stars. Type I Cepheids have chemical abundances roughly like those of the sun, but type II Cepheids are poor in elements heavier than helium. That means the gases in type II Cepheids are not as opaque as the gases in type I Cepheids. The all-important energy flowing outward can escape more easily in type II Cepheids, and they reach a slightly different equilibrium. For stars of the same period of pulsation, type II Cepheids are less luminous, as you can see from the graph in Figure 12-14.

In the H–R diagram, the RR Lyrae stars lie at the lower end of the instability strip. They are a bit smaller and hotter than Cepheids, but they pulsate for the same reason.



■ **Figure 12-14**

More massive stars are larger and more luminous and pulsate with longer periods than less massive stars. Consequently there is a period–luminosity relation: Type I and type II Cepheids have slightly different chemical compositions. The RR Lyrae stars have lower luminosities and shorter periods.

Period Changes in Variable Stars

Some Cepheids have been observed to change their periods of pulsation, and those changes are evidence that stars really do evolve.

The evolution of a star may carry it through the instability strip a number of times, and each time it can become a variable star. If you could watch a star as it entered the instability strip, you could see it begin to pulsate. Similarly, if you could watch a star leave the instability strip, you would see it stop pulsating.

Such an observation would be dramatic evidence that the stars are evolving. But, stars evolve so slowly that these events are rare.

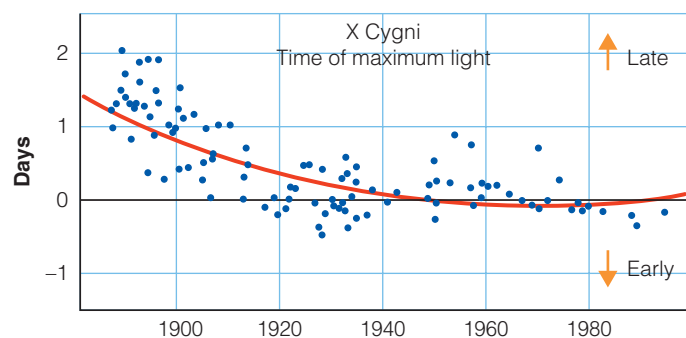
One famous Cepheid, RU Camelopardalis, was observed to stop pulsating temporarily. Its pulsations died away in 1966, and many astronomers assumed that it had stopped pulsating because it was leaving the instability strip, but its pulsations resumed in 1967, so that star's exact situation is not well understood. Remember your Favorite Star, Polaris? It may be going through

a similar change now, although it does not lie near the edge of the instability strip in the H–R diagram. There may be other factors affecting the evolution of Polaris that astronomers have not discovered yet.

Clearer evidence of stellar evolution can be found in the slowly changing periods of Cepheid variables. Even a tiny change in period can become easily observable because it accumulates, just as a clock that gains a second each day becomes obviously fast over a time as long as a year. Some Cepheids have periods that are growing shorter, and others have periods that are growing longer. These changes occur because the stars are evolving and changing their average radii; contraction shortens the period, and

expansion lengthens the period. The star X Cygni, for example, has a period that is gradually growing longer (■ Figure 12-15). These changes in the periods of pulsating stars provide definite evidence that the stars are evolving.

Some other kinds of variable stars lie outside the instability strip because their pulsation is driven by different mechanisms. It is sufficient here to discuss the Cepheids. They are common, they illustrate important ideas about stellar structure, and their changing periods make stellar evolution clearly evident. Also, you will use Cepheids in later chapters to study the distances to galaxies and the fate of the universe.



■ **Figure 12-15**

Like a clock running just a bit slow, the Cepheid variable star X Cygni has been reaching maximum brightness later and later for most of this century. This is shown by the upward curve in this graph of its observed minus predicted times of maximum brightness. As it evolves to the right across the instability strip, it is slowly expanding, and its period is growing longer by 1.46 seconds per year.

SCIENTIFIC ARGUMENT

What evidence can you cite to show that stars really are evolving?

Some processes occur so slowly that they cannot be observed over a human lifetime, so scientists must infer the process from observations. Stellar evolution occurs over billions of years, but because astronomers can plot H–R diagrams of star clusters having different ages, they can see how stellar evolution affects the stars. The H–R diagrams can be assembled into a sequence that makes stellar evolution obvious. Variable stars provide further evidence because tiny changes in radius produce correspondingly tiny changes in period of pulsation. Because those changes accumulate and make the stars run “fast” or “slow,” astronomers can detect the effect of stellar evolution.

Now build a scientific argument that is based on theory. **How do stellar models allow astronomers to understand why Cepheid and RR Lyrae stars pulsate?**

What Are We? Snapshooters

A human lifetime is less than a century, and that is a mere flicker of a moment in the history of the universe. What we see in the sky during our lives is just a snapshot that freezes the action. The stars form gradually and evolve over billions of years. We humans see none of that action. Our snapshot shows us the many stages of star birth and evolution, but we see

almost none of the changes through which stars pass.

Look again at Section 1-2, “When Is Now?” The entire 10,000-year history of human civilization is only a tiny fraction of the history of the universe. In that time, a few of the most massive stars may have evolved slightly, but the vast majority of stars have not changed since

humans on Earth began building the first cities.

Only by the application of human ingenuity have astronomers figured out how stars work, how they are born, how they evolve, and, as you will see in the next chapter, how they die. Our human life spans are only snapshots, but they reveal that we are part of a complex and evolving universe.

Study and Review

Summary

- ▶ Astronomers compute **stellar models** (p. 234) of the interiors of stars based on four simple laws of stellar structure. Two of the laws are the **conservation of mass law** (p. 233) and the **conservation of energy law** (p. 233). The third, the law of hydrostatic equilibrium, says that the star must balance the weight of its layers by its internal pressure. The fourth law says that energy can flow outward only by conduction, convection, or radiation.
- ▶ Mathematical stellar models show how rapidly a star uses its fuel in each layer, and that allows astronomers to step forward in time and follow the evolution of the star as it ages.
- ▶ There is a main sequence of stellar luminosities and temperatures because stars support their weight by hydrogen fusion. As energy flows outward, it heats the gas of the star, and pressure in the gas balances the inward pull of gravity.
- ▶ The mass–luminosity relation for main-sequence stars is explained by the requirement that a star support the weight of its layers by its internal pressure. The more massive a star is, the more weight it must support, and the higher its internal pressure must be. To keep its pressure high, it must be hot and generate large amounts of energy. Thus, the mass of a star determines its luminosity.
- ▶ Extremely massive stars are quite rare. Contracting gas clouds tend to fragment and produce pairs, groups, or clusters of stars and not extremely massive stars. Also, massive stars tend to blow matter away in strong stellar winds, and that rapidly reduces their mass.
- ▶ Stars less massive than 0.08 solar mass can't get hot enough to fuse hydrogen. Objects less massive than this become **brown dwarfs** (p. 237) and slowly cool as they radiate away their thermal energy. Many brown dwarfs have been observed.
- ▶ The **zero-age main sequence (ZAMS)** (p. 238) is the line in the H–R diagram where contracting stars begin fusing hydrogen and reach stability. As a star ages, it moves slightly upward and to the right, making the main sequence a band rather than a narrow line.
- ▶ The life expectancy of a main-sequence star depends on its mass. The more massive stars have more fuel but use their fuels rapidly and remain on the main sequence only a few million years. The sun, a medium-mass star, will last a total of about 10 billion years, and the least massive stars can survive for many hundreds of billion years.
- ▶ When a main-sequence star exhausts its hydrogen, its core contracts, and it begins to fuse hydrogen in a shell around its core. The outer parts of the star—its envelope—swell, and the star becomes a giant. Because of this expansion, the surface of the star cools, and it moves toward the right in the H–R diagram. The most massive stars move across the top of the diagram as supergiants.
- ▶ Because the core of a giant star contracts and the envelope expands, the average density of the star is very low, but the core, where the nuclear fusion occurs, is small and very dense.
- ▶ When the core of the star becomes hot enough, helium fusion, known as the **triple alpha process** (p. 242), begins first in the core and then in a shell. This causes the star to describe a loop in the giant region of the H–R diagram.
- ▶ If the matter in the core becomes **degenerate** (p. 241) before helium ignites, the pressure of the gas does not depend on its temperature, and when helium ignites, the core explodes in the **helium flash** (p. 242). Although the helium flash is violent, the star absorbs the extra energy and quickly brings the helium-fusing reactions under control.
- ▶ Helium fusion produces carbon and oxygen. Other nuclear reactions, which are not important sources of energy, slowly cook the matter during helium fusion and produce small amounts of heavy elements.
- ▶ If a star is massive enough, it can ignite carbon and other fuels after helium fusion. Each fuel fuses more rapidly, producing heavier and heavier elements.
- ▶ Because all the stars in a cluster have about the same chemical composition and age, you can see the effects of stellar evolution in the H–R diagram of a cluster. Massive stars evolve faster than low-mass stars, so in a given cluster the most massive stars leave the main sequence first.
- ▶ There are two types of star clusters. **Open clusters** (p. 248) contain 10 to 1000 stars and have an open, transparent appearance. **Globular clusters** (p. 248) contain 10^5 to 10^6 stars densely packed into a spherical shape. The open clusters tend to be young to middle aged, but globular clusters tend to be as old as 11 billion years. Also, globular clusters tend to be poor in elements heavier than helium.
- ▶ You can judge the age of a cluster by looking at the **turnoff point** (p. 248), the location on the main sequence where the stars turn off to the right and become giants. The life expectancy of a star at the turnoff point equals the age of the cluster.
- ▶ H–R diagrams of old star clusters such as globular clusters show how giant stars ignite helium fusion in their cores and evolve to the left in the diagram along the **horizontal branch** (p. 249).
- ▶ **Variable stars** (p. 247) are those that change in brightness. **Intrinsic variable stars** (p. 247) change in brightness because of internal processes and not because they are member of eclipsing binaries.
- ▶ The **Cepheid** and **RR Lyrae variable stars** (p. 247) are intrinsic variables with properties that lie in an **instability strip** (p. 250) in the H–R diagram; they contain a layer in their envelopes that stores and releases energy as they expand and contract. Stars outside the instability strip do not pulsate because the layer is too deep or too shallow to make the stars unstable.
- ▶ The Cepheids obey a **period–luminosity relation** (p. 247) because more massive stars, which are more luminous, are larger and pulsate more slowly.
- ▶ Some Cepheids have periods that are slowly changing, showing that the evolution of the star is gradually changing the star's average radius and thus its period of pulsation. Thus, some intrinsic variable stars show direct evidence of stellar evolution.

Review Questions

1. Why is there a main sequence?
2. Why is there a lower end to the main sequence? Why is there an upper end?
3. What is a brown dwarf?
4. Why is there a mass–luminosity relation?
5. Why does a star's life expectancy depend on mass?
6. Why do expanding stars become cooler and more luminous?
7. What causes the helium flash? Why does it make it difficult for astronomers to understand the later stages of stellar evolution?
8. How do some stars avoid the helium flash?
9. Why are giant stars so low in density?
10. Why are lower-mass stars unable to ignite more massive nuclear fuels such as carbon?

- How can you estimate the age of a star cluster?
- How do star clusters confirm that stars evolve?
- How do some variable stars show that stars are evolving?
- How Do We Know?** How can mathematical models allow scientists to study processes that are hidden from human eyes or happen too fast or too slowly for humans to experience?

Discussion Questions

- How do you know that the helium flash occurs if it cannot be observed? Can you accept an event as real if you can never observe it?
- Can you think of ways that chemical differences could arise in stars in a single star cluster? Consider the mechanism that triggered their formation.

Problems

- In the model shown in Figure 12-2, how much of the sun's mass is hotter than 13,000,000 K?
- What is the life expectancy of a 16-solar-mass star? Of a 50-solar-mass star?
- How massive could a star be and still survive for 5 billion years?
- If the sun expanded to a radius 100 times its present radius, what would its density be? (*Hint:* The volume of a sphere is $\frac{4}{3}\pi R^3$.)
- If a giant star 100 times the diameter of the sun were 1 pc from Earth, what would its angular diameter be? (*Hint:* Use the small-angle formula, in Chapter 3.)
- What fraction of the volume of a 5-solar-mass giant star is occupied by its helium core? (*Hints:* See Figure 12-9. The volume of a sphere is $\frac{4}{3}\pi R^3$.)
- If the stars at the turnoff point in a star cluster have masses of about 4 solar masses, how old is the cluster?
- If an open cluster contains 500 stars and is 25 pc in diameter, what is the average distance between the stars? (*Hints:* On average, what share of the volume of the cluster surrounds each star? The volume of a sphere is $\frac{4}{3}\pi R^3$.)
- Repeat Problem 8 for a typical globular cluster containing a million stars in a sphere 25 pc in diameter.
- If a Cepheid variable star has a period of pulsation of 2 days and its period increases by 1 second, how late will it be in reaching maximum light after 1 year? After 10 years? (*Hint:* How many cycles will it complete in a year?)

Learning to Look

- In the photograph of the Pleiades on page 249 there are no bright red stars. Use the H-R diagram to explain why the brightest stars are blue. Have there ever been bright red stars in this cluster?
- Look at the photograph of the star cluster M67 on page 249. Why are there no bright blue stars in this cluster?
- The star cluster in the photo at the right contains many hot, blue, luminous stars. Sketch its H-R diagram and discuss its probable age.



NASA/Walborn, Maiz-Apellaniz, and Barba

13

The Deaths of Stars



Visual-wavelength image

Guidepost

Perhaps you were surprised in earlier chapters to learn that stars are born and grow old. Modern astronomers can tell the story of the stars right to the end. Here you will learn how stars die, and as you follow the story you will see how astronomers have tested their theories against evidence to answer four essential questions:

— **How will the sun die?**

— **Why are there so many white dwarf stellar remnants?**

— **What happens if an evolving star is in a binary system?**

— **How do massive stars die?**

Astronomy is exciting because it is about us. As you think about the deaths of stars, you are also thinking about the safety of Earth as a home for life and about the ultimate fate of our sun, our Earth, and the atoms of which you are made.

This nebula cataloged as NGC 2438 was produced by an aging sun-like star that swelled to become a giant and then ejected its outer layers into space. Here red emission is produced by nitrogen atoms, green by hydrogen, and blue by oxygen. (NASA, ESA, Hubble Heritage team, and K. Noll, STScI)

GRAVITY IS PATIENT. In the previous chapter you saw how stars resist their own gravity by generating energy through nuclear fusion. The energy keeps their interiors hot, and the resulting high pressure balances gravity and prevents the stars from collapsing. However, stars have only so much fuel, and it eventually runs out. When the stars exhaust their fuel, gravity wins, and the stars die (■ Figure 13-1).

The mass of a star is critical in determining its fate. Lower-mass stars like the sun die relatively gentle deaths, but massive stars explode violently. In addition, stars that orbit close to another star can have their evolution modified in peculiar ways. To follow the evolution of stars to their graves, you can sort the stars into two categories: lower-main-sequence stars, including the sun, and upper-main-sequence stars.

13-1 Lower-Main-Sequence Stars

THE STARS OF THE LOWER MAIN SEQUENCE have relatively low masses, and they face similar fates as they exhaust their nuclear fuels.



As you learned in the previous chapter, when a star exhausts one nuclear fuel, its interior contracts and grows hotter until the next nuclear fuel ignites. The interior of a star heats up as contraction converts gravitational energy into thermal energy. That presents a problem for lower-main-sequence stars. Low-mass stars don't have a lot of gravitational energy, so they can't get very hot, and that limits the fuels they can ignite. The lowest-mass stars, for example, cannot get hot enough to ignite helium fusion.

As you will learn in the next sections, structural differences divide the lower-main-sequence stars into two subgroups—very-low-mass stars and medium-mass stars such as the sun. The critical difference between the two groups is the extent of interior convection (see Figure 11-15). If the star is convective throughout its interior, so that the hydrogen fuel is constantly mixed, the resulting evolution of the star is strongly affected.

Red Dwarfs

Stars less massive than about 0.4 solar mass—the red dwarfs—can survive a long time. They have very small masses, and consequently they have very little weight to support. Their pressure–temperature thermostats are set low, and they consume their hydrogen fuel very slowly. If you calculate the life expectancy of one of these stars (see Chapter 12), you will discover a red dwarf can be expected to live more than ten times longer than the sun. Furthermore, they are totally convective, and that mixes the interiors of those stars like pots of soup that are constantly stirred. Hydrogen is consumed and helium accumulates uniformly throughout these lowest-mass stars, and that has two important consequences for them.

First, because red dwarf stars are completely mixed and can fuse all their hydrogen, their lives are extra prolonged. Models of a 0.1-solar-mass red dwarf predict it would take 2 billion years to contract to the main sequence and 6 trillion years (6000 billion years) to use up its hydrogen fuel.

The second consequence is that red dwarfs use up their hydrogen uniformly throughout their

■ **Figure 13-1**

Astronomers find evidence of dying stars all around the sky. This small nebula formed within the last few thousand years when an aging giant star expelled its outer layers. The remains of the star collapsed to form a hot white dwarf at the center of the nebula. The sun may suffer this fate in about 5 billion years. (NASA, ESA, and K. Noll, STScI)

interiors. That means they never develop a hydrogen fusion shell, and they never become giant stars. They slowly convert their hydrogen into helium, a fuel they are not massive enough to ignite, and will finally die slow, unremarkable deaths by contracting to form white dwarfs.

You will learn in a later chapter about evidence that the universe is only about 14 billion years old, so no red dwarf should have exhausted its fuel yet. Every red dwarf that has ever been born is still a main sequence star, still fusing hydrogen into helium, still shining. Then why are there so many white dwarfs? There must be another way to make white dwarfs.

Sun-like Stars

Stars like the sun with masses between roughly 0.4 and 4 solar masses* fuse hydrogen, and later, helium, but they cannot get hot enough to ignite carbon, the next fuel in the sequence (see Table 12-3). When they reach that impasse, they can no longer maintain their stability, and for a second time their interiors contract while their envelopes expand, turning them into red giants again. The carbon–oxygen core is a dead end for these stars.

As the helium fusion shell burns outward, it leaves its ashes behind, and that increases the mass of the carbon-oxygen core. Because the core can't get hot enough to fuse carbon, it cannot resist the weight pressing down on it, so it contracts. The energy released by the contracting core, plus the energy generated in the helium- and hydrogen-fusion shells, flows outward and makes the envelope of the star expand and cool further.

This forces the star to become a very large giant the second time around. Its radius may become as large as the radius of Earth's orbit, and its surface can become as cool as 2000 K. Such a star can lose large amounts of mass from its surface.

Mass Loss from Sun-like Stars

It's not hard to find evidence that stars like the sun lose mass. Observations show that the sun itself is losing mass through the solar wind, a gentle breeze of gas that blows outward from the solar corona and carries mass into space. The sun loses only about 0.001 solar mass per billion years. Even over the entire lifetime of the sun, the solar wind would not significantly reduce the sun's mass.

The spectra of stars contain clear evidence of mass loss. Ultraviolet and X-ray spectra of many stars reveal strong emission lines, and you can use Kirchhoff's laws to conclude that the star's outer layers must be highly ionized. That means the stars must have hot chromospheres and coronas like the sun's and must have stellar winds blowing outward. You can find further evidence in the spectra of some giant stars, which contain

* This mass limit is uncertain, as are many of the masses stated here. The evolution of stars is highly complex, and such parameters are not precisely known.

blueshifted absorption lines. The blueshifts are Doppler shifts produced as the gas flowing out of the star moves toward Earth.

Giant stars lose mass much more rapidly than the sun. Because the spectra of some of these stars do not show the characteristic X-ray emission, you must assume that they do not have hot coronas; but other processes could drive mass loss. Giant stars are so large that gravity is weak at their surfaces, and convection in the cool gas can drive shock waves outward that propel mass loss. In addition, some giants are so cool that specks of carbon dust condense in their atmospheres, just as soot can condense in a fireplace. The pressure of the star's radiation can push this dust and any atoms that collide with the dust completely out of the star.

Another process that can cause mass loss in giant stars is periodic eruptions in the helium fusion shell. The triple-alpha process that fuses helium into carbon is extremely sensitive to temperature, and that can make the helium-fusion shell so unstable that it experiences eruptions called **thermal pulses**. Every few hundred thousand years, the shell can erupt and suddenly produce energy equivalent to a million times the luminosity of the sun. Almost all of that energy goes into lifting the outer layers of the star and driving gas away from the surface.

Rapid mass loss can affect stars dramatically. Observations show that some giant stars are losing mass so rapidly that they can shed an entire solar mass in only 100,000 years, a short time in the evolution of a star. That means that a star that began its existence on the main sequence with a mass of 8 solar masses might reduce its mass to only 3 solar masses in half a million years once it becomes a giant.

Stellar mass loss confuses the story of stellar evolution. Astronomers would like to be able to say that stars more massive than a certain limit will evolve one way, and stars less massive will evolve another way. But giant stars may lose enough mass to alter their own evolution. As a result, you need to consider both the initial mass a star has on the main sequence and the mass it retains after later stages of mass loss. Because astronomers don't know exactly how effective mass loss is, it is difficult to be exact about the mass limits in any discussion of stellar evolution.

Planetary Nebulae

When a medium-mass star like the sun becomes a distended giant, its atmosphere cools. As it cools, it becomes more opaque, and light has to push against it to escape. At the same time, the fusion He shell becomes so narrow it is unstable and begins to flare, which also pushes the atmosphere outward. Because of this outward pressure, an aging giant can expel its outer atmosphere in repeated surges to form one of the most beautiful objects in astronomy, a **planetary nebula**, so called because through a small telescope some of them look like the greenish-blue disk of a planet like Uranus or Neptune. In fact, a planetary nebula has nothing to do with a planet. It is composed of ionized gases expelled by a dying star.

Read **The Formation of Planetary Nebulae** on pages 260–261 and notice four things:

- 1 You can understand what planetary nebulae are like by using simple observational principles such as Kirchhoff's laws and the Doppler effect.
- 2 Notice the model that astronomers have developed to explain planetary nebulae. The real nebulae are more complex than the simple model of a slow wind and a fast wind, but that model provides a way to organize the observed phenomena.
- 3 Oppositely directed jets (much like bipolar flows from protostars) produce many of the asymmetries seen in planetary nebulae.
- 4 The star itself must contract into a white dwarf.

Most astronomy books say that the sun will form a planetary nebula, but that is questionable. To ionize the gas and light up a planetary nebula, a star must become a white dwarf with a temperature of at least 25,000 K. Mathematical models show that a collapsing star of less than 0.55 solar mass can take as long as a million years to heat up enough to ionize its nebulae, and by that time, the expelled gases are long gone. Models of the sun are not precise enough to indicate how much mass will be left once it ejects its outer layers. If it is left with too little mass, it may heat too slowly to make a planetary nebula. Also, some research suggests that to eject a planetary nebula, a star needs a close binary companion to speed up its spin. The sun, of course, has no close binary companion. This is an area of active research, and there are no firm conclusions.

Medium-mass stars die by ejecting gas into space and contracting into white dwarfs. You have found evidence regarding the deaths of some medium-mass stars in observations of planetary nebulae. Now you can turn your attention to the evidence revealed by the white dwarf remnants themselves.

White Dwarfs

White dwarfs are among the most common stars. The census of stars in Chapter 9 revealed that white dwarfs and red dwarfs, although very faint, are common (page 187). Now you can recognize white dwarfs as the remains of medium-mass stars that fused hydrogen and then helium, failed to ignite carbon, drove away their outer layers, and finally collapsed to form white dwarfs. The billions of white dwarfs in our galaxy are the remains of medium-mass stars like the sun.

The first white dwarf discovered was the faint companion to one of your Favorite Stars, Sirius. In that visual binary system, the bright star is Sirius A. The white dwarf, Sirius B, is 10,000 times fainter than Sirius A. The orbital motions of the stars (shown in Figure 9-15) reveal that the white dwarf's mass is 0.98 solar mass, and its blue-white color tells you that its

surface is hot, about 25,000 K. Although it is very hot, it has a very low luminosity, so it must have a small surface area—in fact, it is roughly the size of Earth. Dividing its mass by its volume reveals that it is very dense—over 2×10^6 g/cm³. On Earth, a teaspoonful of Sirius B material would weigh more than 11 tons (■ Figure 13-2). Basic observations and simple physics lead to the conclusion that white dwarfs are astonishingly dense.

A normal star is supported by energy flowing outward from its core, but a white dwarf cannot generate energy by nuclear fusion. It has exhausted its hydrogen and helium fuels and converted them into carbon and oxygen. When a star collapses into a white dwarf, it converts gravitational energy into thermal energy. Its interior becomes very hot, but it cannot get hot enough to fuse its carbon-oxygen interior. Instead the star contracts until it becomes degenerate. Although a tremendous amount of energy flows out of its hot interior, it is not the energy flow that supports the star. As you learned in the previous chapter, a white dwarf is supported against its own gravity by the inability of its degenerate electrons to pack into a smaller volume. In this case, the properties of white dwarfs, objects as big as Earth, are determined by the properties of subatomic particles. Astronomers often find that the causes of natural phenomena lead step by step into the subatomic world (**How Do We Know? 13-1**).



■ **Figure 13-2**

The degenerate matter from inside a white dwarf is so dense that a lump the size of a beach ball would, transported to Earth, weigh as much as an ocean liner.

Toward Ultimate Causes

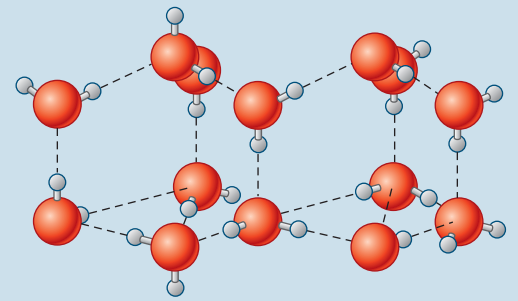
How do scientist's search for natural causes lead into the world of subatomic particles? Scientists search for causes. They are not satisfied to know that a certain kind of star dies by exploding. They want to know why it explodes. They want to find the causes for the natural events they see, and that search for ultimate causes often leads into the atomic world.

For example, why do icebergs float? When water freezes, it becomes less dense than liquid water, so it floats. That answers the question, but you can search for a deeper cause.

Why does ice float? Why is it less dense than water? Water molecules are made up of two hydrogen atoms bonded to an oxygen atom, and the oxygen is so good at attracting electrons, the hydrogen atoms are left needing a bit more negative charge, and they are attracted to atoms in nearby molecules.

That means the hydrogen atoms in water are constantly trying to stick to other molecules. When water is warm, the thermal motion prevents these hydrogen bonds from forming; but when water freezes, the hydrogen atoms link the water molecules together. Because of the angles at which the bonds form, the molecules leave open spaces between molecules, and that makes ice less dense than water.

But scientists can continue their search for causes. Why do electrons have negative charge? What is charge? Nuclear particle physicists are trying to understand those properties of matter. Sometimes the properties of very large things such as supernovae are determined by the properties of the tiniest particles. Science is exciting because the simple observation that ice floats in your lemonade can lead you toward ultimate causes and some of the deepest questions about how nature works.



Ice has a low density and floats because of the way electrons (blue) link to oxygen (red) when water freezes.

The interior of a white dwarf is mostly carbon and oxygen nuclei floating among a whirling storm of degenerate electrons. It is these degenerate electrons that exert the pressure needed to support the star's weight, but most of the star's mass is represented by the carbon and oxygen ions. Theory predicts that, as the star cools, these ions lock together to form a crystal lattice, so there may be some truth in the image of aging white dwarfs as great crystals of carbon and oxygen. Near the surface, where the pressure is lower, a layer of ionized gases makes up a hot atmosphere.

The tremendous surface gravity of a white dwarf—100,000 times that of Earth—affects its atmosphere in strange ways. The heavier atoms in the atmosphere tend to sink, leaving the lightest gases at the surface. Astronomers see some white dwarfs with atmospheres of almost pure hydrogen, whereas others have atmospheres of nearly pure helium (gas that was never close enough to the core to be fused into carbon). Still others, for reasons not well understood, have atmospheres that contain traces of heavier atoms. In addition, the powerful surface gravity pulls the white dwarf's atmosphere down into a very shallow layer. If Earth's atmosphere were equally shallow, people on the top floors of skyscrapers would have to wear oxygen masks.

Clearly, a white dwarf is not a true star. It generates no nuclear energy, is almost totally degenerate, and, except for a

thin layer at its surface, contains no gas. Instead of calling a white dwarf a star, you can call it a **compact object**. In the next chapter, you will meet two other types of compact objects that are remnants of burned-out stars—neutron stars and black holes.

A white dwarf's future is bleak. Degenerate matter is a very good thermal conductor, so heat flows to the surface and escapes into space, and the white dwarf gets fainter and cooler, so the point representing its luminosity and temperature moves downward and to the right in the H-R diagram. As it radiates energy into space, its temperature gradually falls, but it cannot shrink any smaller because its degenerate electrons cannot get closer together. Because the white dwarf contains a tremendous amount of heat, it needs billions of years to radiate that heat through its small surface area. Eventually, such objects may become cold and dark, so-called **black dwarfs**. Our galaxy is not old enough to contain black dwarfs. The coolest white dwarfs in our galaxy are just a bit cooler than the sun.

One more important and interesting fact about white dwarfs is predicted by mathematical models. The equations predict that if you added mass to a white dwarf, its radius would *shrink*, because added mass would increase its gravity and squeeze it tighter. If you added enough to raise its total mass to about 1.4 solar masses, its radius would shrink to zero

The Formation of Planetary Nebulae



1 Simple observations tell astronomers what planetary nebulae are like. Their angular size and their distances indicate that their radii range from 0.2 to 3 ly. The presence of emission lines in their spectra assures us that they are excited, low-density gas. Doppler shifts show they are expanding at 10 to 20 km/s. If you divide radius by velocity, you find that planetary nebulae are no more than about 10,000 years old. Older nebulae evidently become mixed into the interstellar medium.

Astronomers find about 3000 planetary nebulae in the sky. Because planetary nebulae are short-lived formations, you can conclude that they must be a common part of stellar evolution. Medium-mass stars up to a mass of about 8 solar masses are destined to die by forming planetary nebulae.

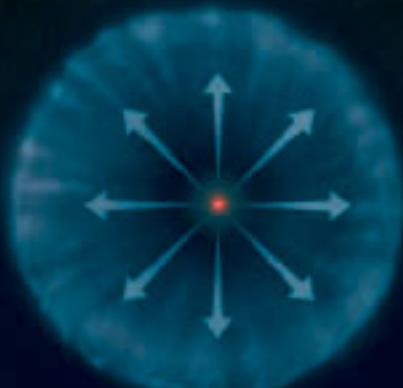
The Helix Nebula is 2.5 ly in diameter, and the radial texture shows how light and winds from the central star are pushing outward.

NASA/JPL-Caltech/ESA

Visual + Infrared

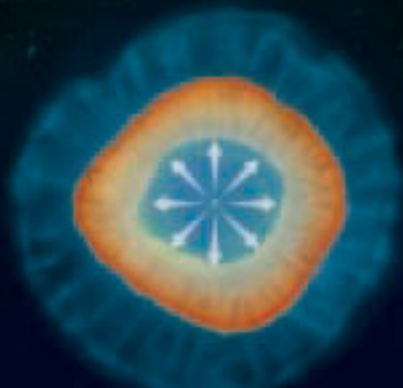
2 The process that produces planetary nebulae involves two stellar winds. First, as an aging giant, the star gradually blows away its outer layers in a slow breeze of low-excitation gas that is not easily visible. Once the hot interior of the star is exposed, it ejects a high-speed wind that overtakes and compresses the gas of the slow wind like a snowplow, while ultraviolet radiation from the hot remains of the central star excites the gases to glow like a giant neon sign.

Slow stellar wind from a red giant



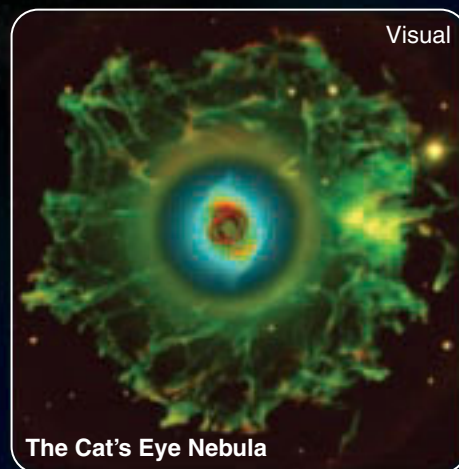
The gases of the slow wind are not easily detectable.

Fast wind from exposed interior



You see a planetary nebula where the fast wind compresses the slow wind.

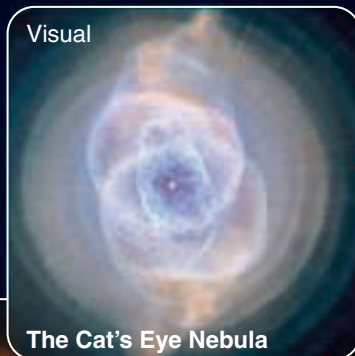
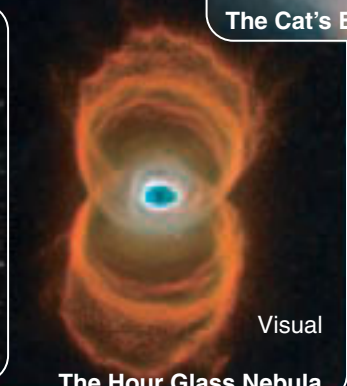
2a The Cat's Eye, below, lies at the center of an extended nebula that must have been exhaled from the star long before the fast wind began forming the visible planetary nebula. See other images of the nebula on opposite page.



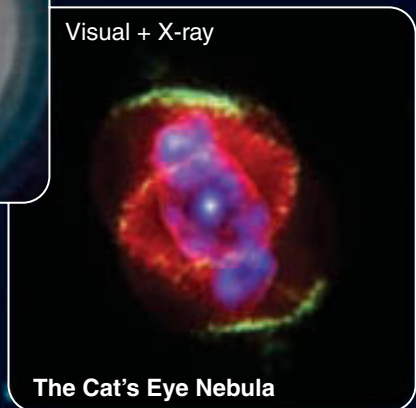
The Cat's Eye Nebula

Roman Corradi/Nordic Optical Telescope

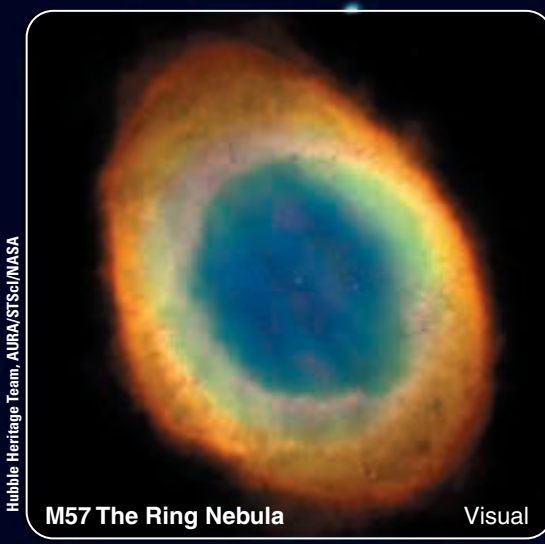
3 Images from the Hubble Space Telescope reveal that asymmetry is the rule in planetary nebulae rather than the exception. A number of causes have been suggested. A disk of gas around a star's equator might form during the slow-wind stage and then deflect the fast wind into oppositely directed flows. Another star or planets orbiting the dying star, rapid rotation, or magnetic fields might cause these peculiar shapes. The Hour Glass Nebula seems to have formed when a fast wind overtook an equatorial disk (white in the image). The nebula Menzel 3, as do many planetary nebulae, shows evidence of multiple ejections.



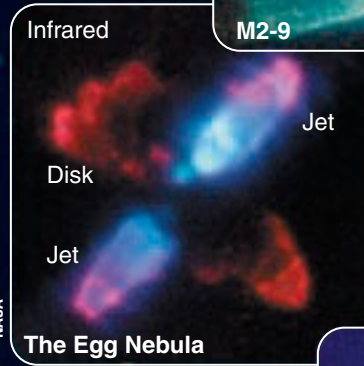
Some shapes suggest bubbles being inflated in the interstellar medium. The Cat's Eye is shown at left, below, and on the facing page.



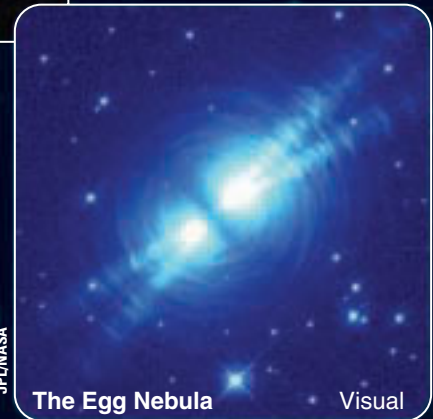
The purple glow in the image above is a region of X-ray bright gas with a temperature measured in millions of degrees. It is apparently driving the expansion of the nebula.



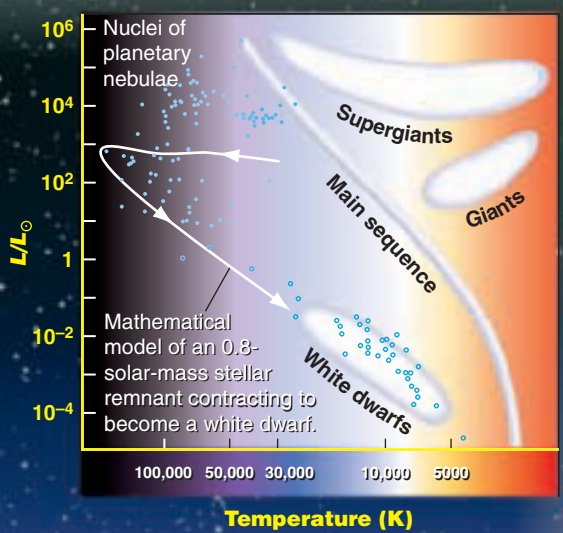
Some planetary nebulae, such as M2-9, are highly elongated, and it has been suggested that the Ring Nebula, at left, is a tubular shape that happens to be pointed roughly at Earth.



At visual wavelengths, the Egg Nebula is highly elongated, as shown below. The infrared image at left reveals an irregular, thick disk from which jets of gas and dust emerge. Such beams may create many of the asymmetries in planetary nebulae.

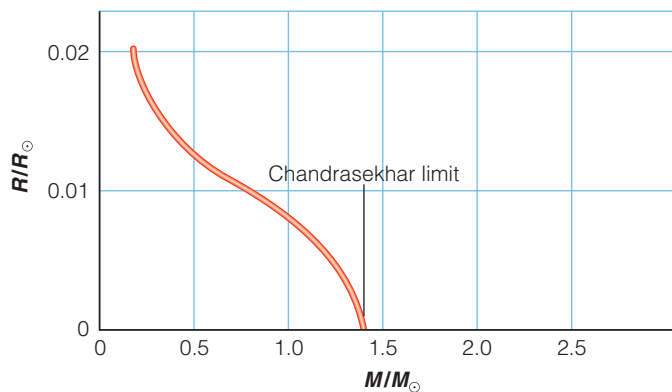


4 Once an aging giant star blows its surface into space to form a planetary nebula, the remaining hot interior collapses into a small, intensely hot object containing a carbon and oxygen interior surrounded by hydrogen and helium fusion shells and a thin atmosphere of hydrogen. The fusion gradually dies out, and the core of the star evolves to the left of the conventional H-R diagram to become the intensely hot nucleus of a planetary nebulae. Mathematical models show that these nuclei cool slowly to become white dwarfs.



(■ Figure 13-3). This is called the **Chandrasekhar limit** after Subrahmanyan Chandrasekhar, the astronomer who discovered it. It seems to imply that a star more massive than 1.4 solar masses cannot become a white dwarf unless it sheds mass in some way.

As you saw earlier in this chapter, aging giant stars do lose mass (■ Figure 13-4). This suggests that stars more massive than the Chandrasekhar limit can eventually die as white dwarfs if they reduce their mass. Theoretical models show that an 8-solar-mass star should be able to reduce its mass to 1.4 solar masses before it collapses. Consequently, a wide range of medium-mass stars eventually die as white dwarfs. No wonder white dwarfs are so common.



■ **Figure 13-3**

The more massive a white dwarf, the smaller its radius. Stars more massive than the Chandrasekhar limit of 1.4 solar masses at the ends of their lives cannot become white dwarfs.

SCIENTIFIC ARGUMENT

What evidence can you cite to show that large numbers of stars die by producing planetary nebula?

You can begin your argument by noting that planetary nebulae are only a light-year or so in radius and that Doppler shifts show that they are expanding at 10 to 20 km/s. Dividing the radius by the velocity tells you that a typical planetary nebula is only about 10,000 years old. That means that the nebulae don't last very long. Nevertheless, astronomers find almost 3000 of them visible in the sky. To be so common but so short lived, planetary nebulae must be produced in large numbers as medium-mass stars blow their outer layers into space.

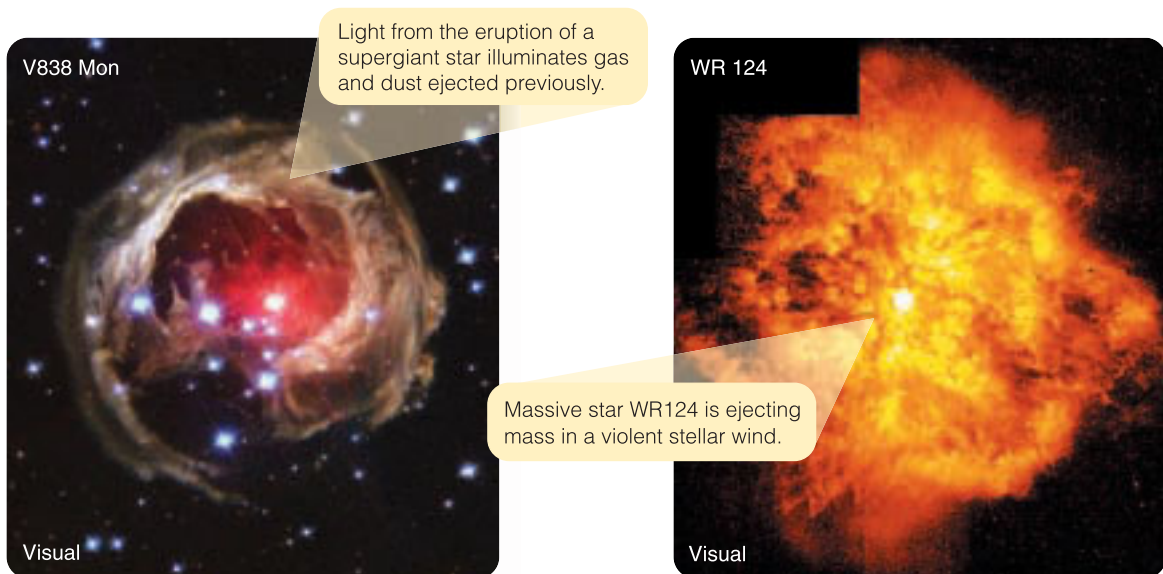
Now review more evidence. **Use Favorite Star Sirius to explain how you know that white dwarfs are very dense.**

13-2 The Evolution of Binary Stars

SO FAR YOU HAVE BEEN THINKING about the deaths of stars as if they were all single objects that never interact. But more than half of all stars are members of binary star systems. Most such binaries are far apart, so one of the stars can swell into a giant and eventually collapse without affecting the companion star. In some binary systems, however, the two stars orbit close together. When the more massive star begins to expand, it interacts with

■ **Figure 13-4**

Stars can lose mass if they are very hot, very large, or both. The massive red supergiant VY Canis Majoris is ejecting gas in loops, arcs, and knots as it ages. A young massive star such as WR124 constantly loses mass into space. Warmed dust in these gas clouds can make them glow in the infrared. (VY Canis Majoris: NASA, ESA, R. Humphreys; WR124: NASA)



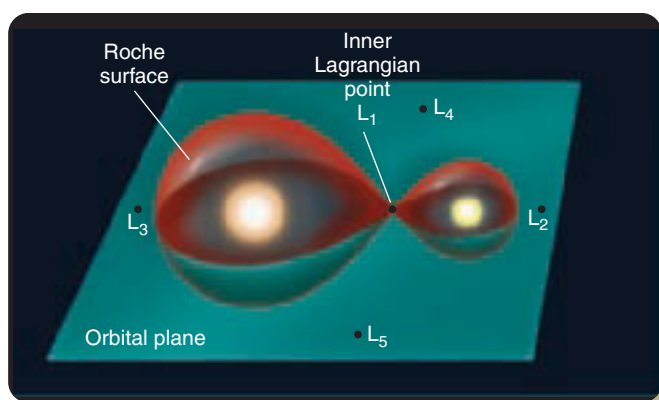
its companion star in complicated ways. These interacting binary stars are fascinating objects, and they are important because they help explain observed phenomena such as nova explosions. In the next chapter, you will see how they can also help astronomers search for black holes.

Mass Transfer

Binary stars can sometimes interact by transferring mass from one star to the other. The gravitational fields of the two stars, combined with the rotation of the binary system, define a dumbbell-shaped volume around the pair of stars called the **Roche lobes**. The gravity of each star controls the motion of matter inside its Roche lobe. The surface of this volume is called the **Roche surface**. The size of the Roche lobes depends on the mass of the stars and on the distance between the stars. If the stars are far apart, the lobes are very large, and the stars easily hang on to their own material. If the stars are close together, however, the lobes are small and can interfere with the evolution of the stars. Matter inside each star's Roche lobe is gravitationally bound to the star, but matter that crosses the Roche surface and leaves a star's Roche lobe can fall into the other star or leave the binary system completely.

The **Lagrangian points** are places in the orbital plane of a binary star system where a bit of matter can reach stability. For astronomers, the most important of these points is the **inner Lagrangian point**, where the two Roche lobes meet (■ Figure 13-5). If matter can leave a star and reach the inner Lagrange point, it can flow onto the other star. Thus, the inner Lagrangian point is the connection through which the stars can transfer matter.

In general, there are only two ways matter can escape from a star and reach the inner Lagrangian point. First, if a



■ **Figure 13-5**

A pair of binary stars control the region of space located inside the Roche surface. The Lagrangian points are locations of stability, with the inner Lagrangian point making a connection through which the two stars can transfer matter.

star has a strong stellar wind, some of the gas blowing away from it can pass through the inner Lagrangian point and be captured by the other star. Second, if an evolving star expands so far that it fills its Roche lobe, which can occur if the stars are close together and the lobes are small, then matter can overflow through the inner Lagrangian point onto the other star. Mass transfer driven by a stellar wind tends to be slow, but mass can be transferred rapidly from an expanding star.

Evolution with Mass Transfer

Mass transfer between binary stars can affect the evolution of both stars in surprising ways. In fact, it provides the explanation of a problem that puzzled astronomers for many years.

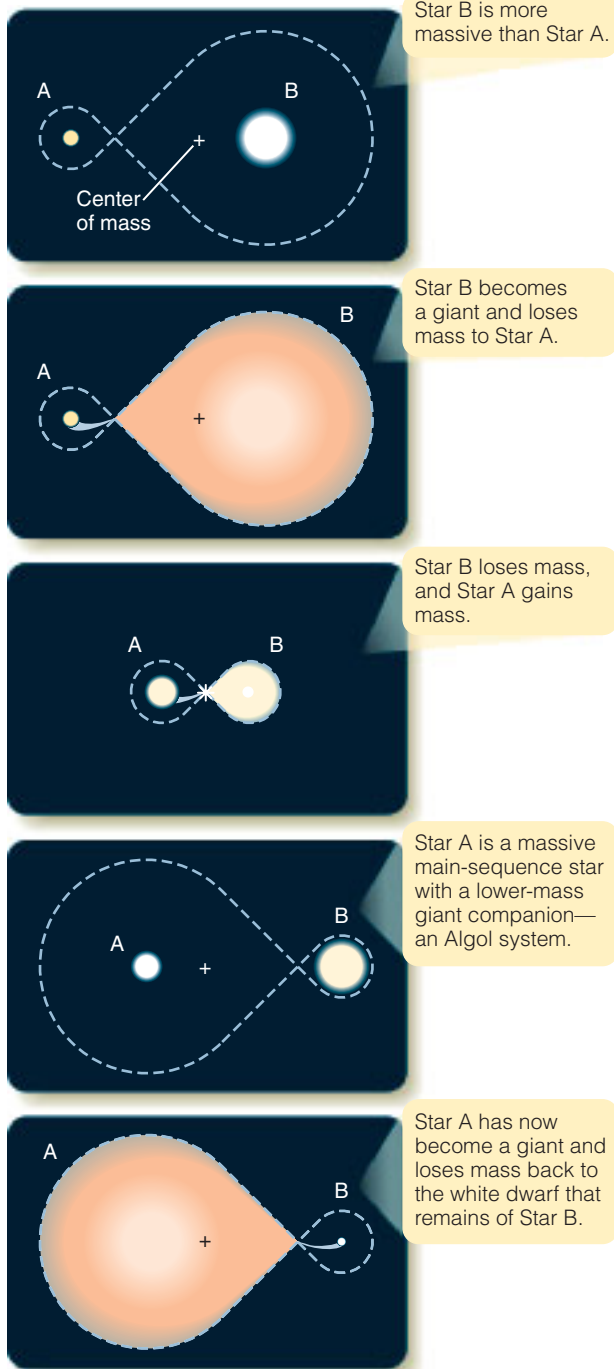
In some binary systems, the less massive star has become a giant, while the more massive star is still on the main sequence. That seems backward. If more massive stars evolve faster than lower-mass stars, how could the low-mass star leave the main sequence first? This is called the Algol paradox, after the binary system Algol (also known as Beta Persei) (see Figure 9-22).

Mass transfer explains how this could happen. Imagine a close binary system that contains a 5-solar-mass star and a 1-solar-mass companion (■ Figure 13-6). The two stars formed at the same time, so the more massive star must evolve faster and leave the main sequence first. When it expands into a giant, it fills its Roche surface and transfers matter to the low-mass companion. The massive star shrinks into a lower-mass star, and the companion gains mass to become a more massive main-sequence star. If you observed such a system after the mass transfer ended, you would see a binary system like Algol, which contains a 5-solar-mass main-sequence star and a 1-solar-mass giant.

Another exotic result of the evolution of close binary systems is the possible merging of the stars. Astronomers see many binaries in which both stars have expanded to fill their Roche surfaces and now spill mass out into space. If the stars are close enough together and expand rapidly enough, theorists believe, the two stars could merge into a single, rapidly rotating giant star. Most giants rotate slowly because they conserved angular momentum and slowed their rotation as they expanded. Examples of rapidly rotating giant stars are known, however, and they are thought to be the result of merged binary stars. Inside the distended envelope of such a star, the cores of the two stars may even continue to orbit each other until friction slows them down and they sink to the center.

Mass transfer can lead to dramatic violence. The first four frames of Figure 13-6 show how mass transfer could have produced a system like Algol. The last frame shows an additional stage in which the giant star has expelled its outer layers and

The Evolution of a Binary System



■ **Figure 13-6**

A pair of stars orbiting close to each other can exchange mass and modify their evolution.

collapsed to form a white dwarf. The more massive companion has expanded and now transfers matter back onto the white dwarf. Such systems can become the site of tremendous explosions. To see how this can happen, you need to consider in detail how mass falls into a star.

Accretion Disks

Matter flowing from one star to another cannot fall directly into the star. Rather, because of conservation of angular momentum, it must flow into a whirling disk around the star.

As you learned in Chapter 5, angular momentum refers to the tendency of a rotating object to continue rotating. All rotating objects possess some angular momentum; and, in the absence of external forces, an object maintains (conserves) its total angular momentum. For a common example, consider a bathtub full of water. Gentle currents in the water give it some angular momentum, but you can't see its slow circulation until you pull the stopper. Then, as the water rushes toward the drain, conservation of angular momentum forces it to form a whirlpool.

In a binary star system, mass transferred through the inner Lagrangian point toward one of the stars must conserve its angular momentum. If the star is small enough, as in the case of a white dwarf, the mass will form a rapidly rotating whirlpool around the star called an **accretion disk** (■ Figure 13-7).

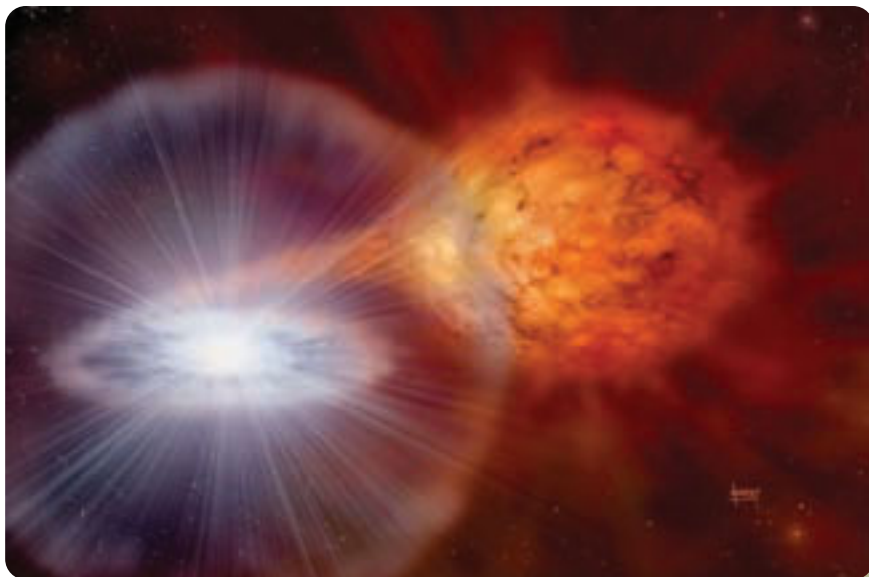
Two important things happen in an accretion disk. First, the gas in the disk grows very hot due to friction and tidal forces. The disk also acts as a brake, shifting angular momentum outward in the disk and allowing the innermost matter to fall into the white dwarf. The interior parts of an accretion disk around a white dwarf are violent places. The temperature of the gas can exceed a million Kelvin, causing the gas to emit X-rays, and the matter falling inward can produce a violent explosion when enough accumulates on the white dwarf.

Nova Explosions

Astronomers occasionally see a **nova**, what seems to be a new star that appears in the sky, grows brighter, then fades away after a few weeks (■ Figure 13-8). In fact, *nova* is the Latin word for “new.” Modern astronomers know that a nova is not a new star but an old star flaring up. After a nova fades, astronomers can photograph the spectrum of the remaining faint point of light. Invariably, they find a short-period spectroscopic binary containing a normal star and a white dwarf. A nova is evidently an explosion involving a white dwarf.

Observational evidence can tell you how nova explosions occur. As the explosion begins, spectra show blueshifted absorption lines, which tells you the gas is dense and coming toward you at a few thousand kilometers per second. After a few days, the spectral lines change to emission lines, telling you the gas has thinned enough to become transparent. The blueshifts remain, so you can conclude that a spherical shell of gas is continuing to expand into space.

Nova explosions occur in binary systems when mass transfers from a normal star through the inner Lagrangian point into an accretion disk around a white dwarf. As the matter loses its angular momentum in the accretion disk, it spirals inward and eventually settles onto the surface of the white dwarf. Because the



■ **Figure 13-7**

Matter from an evolving red giant falls into a white dwarf and forms a whirling accretion disk. Friction and tidal forces can make the disk very hot. Such systems can lead to nova explosions on the surface of the white dwarf as shown in this artist's impression. (David A. Hardy, www.astroart.org, and PPARC)

matter came from the surface of a normal star, it is rich in unused nuclear fuel, mostly hydrogen. As it accumulates on the surface of the white dwarf, it forms a layer of unprocessed fuel.

As the layer of fuel grows deeper, it becomes hotter and denser. Compressed by the white dwarf's gravity, the gas becomes degenerate, much like the core of a sun-like star approaching the helium flash. In such a gas, the pressure–temperature thermostat does not work, so the layer of unfused hydrogen is a thermonuclear bomb waiting to explode. By the time the white dwarf has accumulated about 100 Earth masses of hydrogen, the temperature at the base of the hydrogen layer reaches millions of degrees, and the density is 10,000 times the density of water. Suddenly, the nuclear reactions of the proton–proton chain begin to fuse the hydrogen, and the energy released drives the

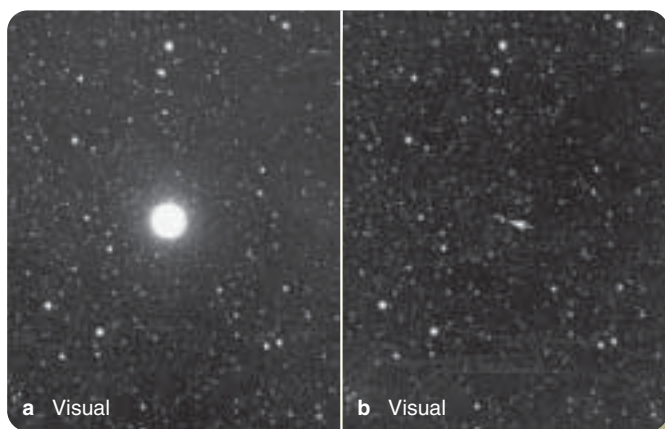
temperature so high that the CNO cycle begins. With no pressure–temperature thermostat to control the fusion, the temperature shoots to 100 million degrees in seconds. The temperature quickly rises high enough to force the gas to expand, and it is no longer degenerate. But it is too late for the pressure–temperature thermostat to cause the non-degenerate gas to become stable. By the time the gas begins to expand, enough energy has been released to blow the surface layers of the white dwarf into space as a violently expanding shell of hot gas, visible from Earth as a nova.

The explosion of its surface hardly disturbs the white dwarf or its companion star. Mass transfer quickly resumes, and a new layer of fuel begins to accumulate. How fast the fuel builds up depends on the rate of mass transfer. Accordingly, you can expect novae (the plural of nova) to repeat each time an explosive layer accumulates. Many novae probably take thousands of years to build an explosive layer, but some take only a few years (■ Figure 13-9).

The End of Earth

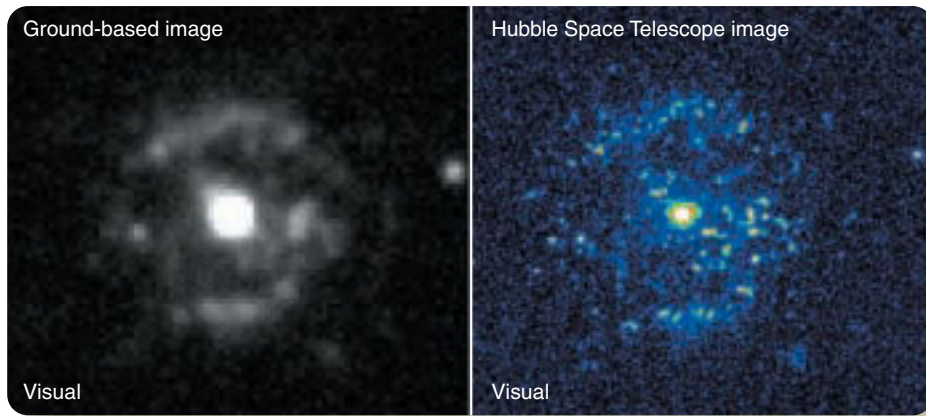
Astronomy is about us. Although this chapter has discussed the deaths of stars, it has also been discussing the future of our planet. The sun is a medium-mass star and will eventually die by becoming a giant, possibly producing a planetary nebula, and collapsing into a white dwarf. That will spell the end of Earth.

Evolutionary models of the sun suggest that it may survive for an additional 6 billion years or so, but it is already growing more luminous as it fuses hydrogen into helium. In about 5 billion years, it will exhaust hydrogen in its core, begin burning hydrogen in a shell, and swell into a red giant star about 30 times its present radius. Later, helium fusion will ignite in the core and the sun will contract somewhat, becoming a horizontal branch star. Then, when the helium fuel is exhausted in its core and helium fusion begins in a shell, the sun will have another episode as a red giant. That second red giant version of the sun will be about as large as the orbit of Earth, so that will mark the end of our world. Before that, the sun's increasing luminosity will certainly evaporate Earth's oceans, drive away the atmosphere, and even vaporize much of Earth's crust. Astronomers are still uncertain about some of the details, but computer models that include



■ **Figure 13-8**

Nova Cygni 1975, near its maximum apparent brightness of about second magnitude, and later when it had declined to about eleventh magnitude. (Photo© UC Regents)



■ **Figure 13-9**

Nova T Pyxididis erupts about every two decades, expelling shells of gas into space. The shells of gas are visible from ground-based telescopes, but the Hubble Space Telescope reveals much more detail. The shell consists of knots of excited gas that presumably form when a new shell collides with a previous shell. (M. Shara and R. Williams, STScI; R. Gilmozzi, ESO; and NASA)

tidal effects predict that the expanding sun eventually will engulf and destroy Mercury, Venus, and Earth. While it is a giant star, the sun will have a strong wind and lose a substantial fraction of its mass into space. The atoms that were once in Earth will be part of the expanding nebula around the sun. Your atoms will be part of that nebula. If the white dwarf remnant sun becomes hot enough, it will ionize the expelled gas and light it (and you) up as a planetary nebula.

There is no danger that the sun will explode as a nova; it has no binary companion. And, as you will see in the next section, the sun is not massive enough to die the violent death of the massive stars.

The most important lesson of astronomy is that we are part of the universe and not just observers. The atoms we are made of are destined to return to the interstellar medium in just a few billion years. That's a long time, and it is possible that the human race will migrate to other planetary systems before then. That might save the human race, but much of our planet will return to being stardust.

SCIENTIFIC ARGUMENT

How does spectroscopic evidence tell you what a nova explosion is like?

For this argument you need to use your knowledge of basic spectroscopy. As soon as a nova is seen, astronomers rush to telescopes to record spectra, and they see blueshifted absorption lines. The blueshifts are Doppler shifts showing that the near side of the object is coming toward Earth. The absorption lines must be formed by fairly dense gas seen through thinner gas, much like the atmosphere of a star, so the surface of the star must be expanding rapidly outward. Later the spectrum becomes an emission spectrum, and Kirchhoff's laws tell you that the gas must have thinned and become transparent. The continued blueshift shows that the expansion is continuing.

Now review the post-explosion evidence. **How do observations of novae long after they have faded provide evidence that white dwarfs are involved?**

13-3 The Deaths of Massive Stars

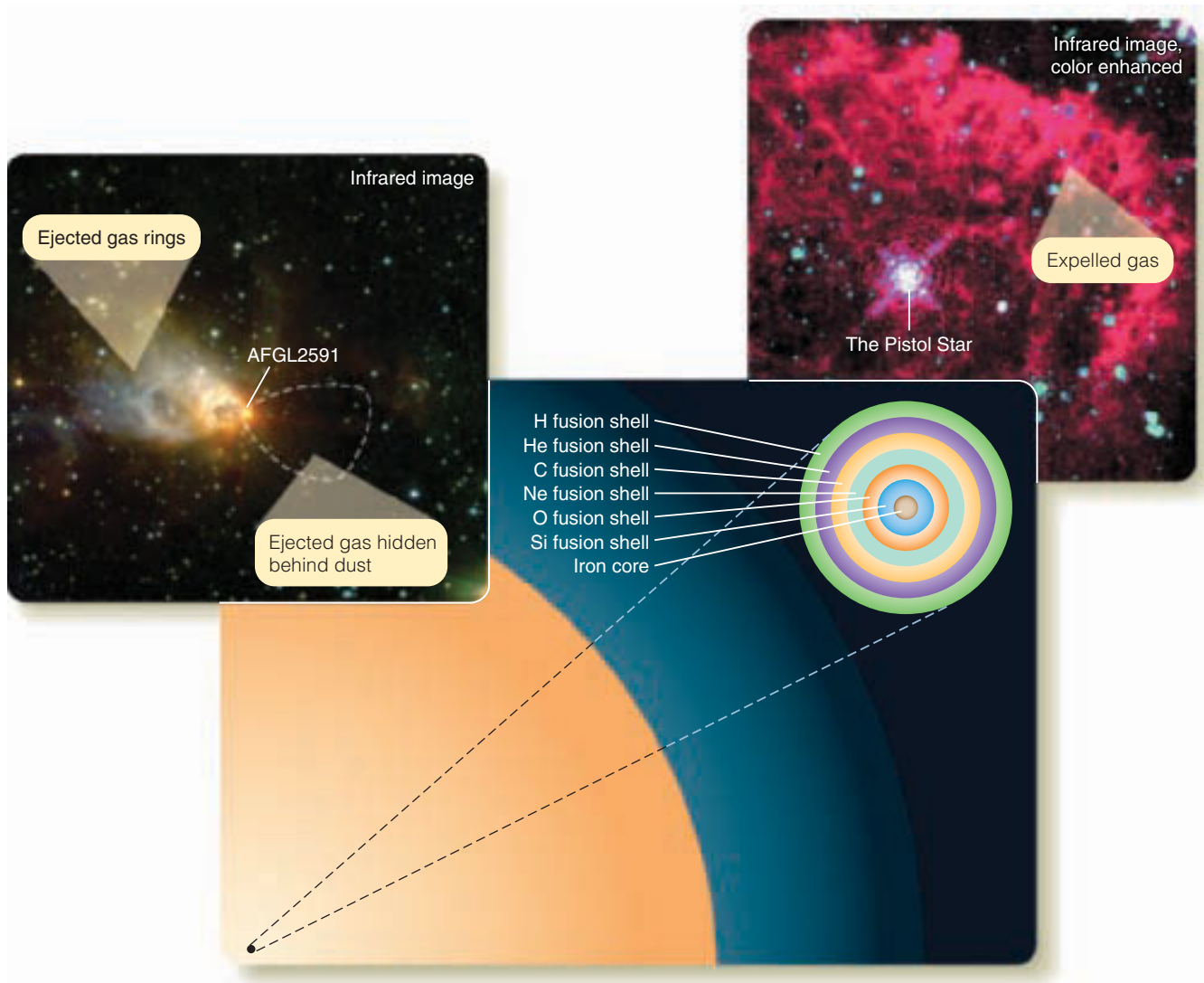
YOU HAVE SEEN that low- and medium-mass stars die relatively quietly as they exhaust their hydrogen and helium and then eject their surface layers, in some cases forming planetary nebulae. In contrast, massive stars live spectacular lives and then destroy themselves in violent explosions.

Nuclear Fusion in Massive Stars

Stars on the upper main sequence have too much mass to die as white dwarfs, but their evolution begins much like that of their lower-mass cousins. They consume the hydrogen in their cores and ignite hydrogen fusion shells; as a result, they expand into giants or, for the most massive stars, supergiants. Next, their cores contract and fuse helium—first in the core and then in a shell, producing a carbon–oxygen core.

A massive star can lose significant mass as it ages; but, if it still has a mass over 4 solar masses when its carbon–oxygen core contracts, it can ignite carbon fusion at a temperature of about 1 billion Kelvin. Carbon fusion produces more oxygen and neon. As soon as the carbon is exhausted in the core, the core contracts, and carbon ignites in a shell. This pattern of core ignition and shell ignition continues with fuel after fuel, and the star develops the layered structure as shown in ■ Figure 13-10, with a hydrogen fusion shell above a helium fusion shell above a carbon fusion shell above . . . After carbon fuses, oxygen, neon, and magnesium fuse to make silicon and sulfur, and then the silicon fuses to make iron.

The fusion of successive nuclear fuels goes faster and faster as the massive star evolves. Recall that massive stars must consume their fuels rapidly to support their great weight, but other factors also cause the heavier fuels like carbon, oxygen, and silicon to fuse at increasing speeds. For one thing, the amount of energy released per fusion reaction decreases as the mass of the fusing atom increases. To support its weight, a star must fuse



■ **Figure 13-10**

Massive stars live fast and die young. The two shown here are among the most massive stars known, containing 100 solar masses or more. They are rapidly ejecting gas into space. (See also Figure 12-3.) The centers of these massive stars develop Earth-size cores (magnified 100,000 times in this figure) composed of concentric layers of gases undergoing nuclear fusion. The iron core at the center leads eventually to a star-destroying explosion. (AFGL 2591: Gemini Observatory/NSF/C. Aspin; The Pistol Star: NASA)

oxygen much faster than it fused hydrogen. Also, there are fewer nuclei in the core of the star by the time heavy nuclei begin to fuse. Four hydrogens make a helium nucleus, and three heliums make a carbon, so there are 12 times fewer nuclei of carbon available for fusion than there were hydrogen. This means the fusion of heavy elements goes very quickly in massive stars (■ Table 13-1). Model calculations indicate that hydrogen core fusion can last 7 million years in a 25-solar-mass star, but that same star will fuse the oxygen in its core in six months and its silicon in a day.

■ **Table 13-1** | **Heavy-Element Fusion in a 25- M_{\odot} Star**

Fuel	Time	Percentage of Lifetime
H	7,000,000 years	93.3
He	500,000 years	6.7
C	600 years	0.008
O	0.5 years	0.000007
Si	1 day	0.00000004

The Iron Core

Heavy-element fusion ends with iron because nuclear reactions that use iron as a fuel cannot produce energy. Nuclear reactions can produce energy if they proceed from less tightly bound nuclei to more tightly bound nuclei. As shown in Figure 8-8, both nuclear fission and nuclear fusion produce nuclei that are more tightly bound than the starting fuel. Look again at Figure 8-8 and notice that iron is the most tightly bound nucleus of all. No nuclear reaction, fission or fusion, that starts with iron can produce a more tightly bound nucleus, and that means that iron is a dead end.

When a massive star develops an iron core, nuclear fusion cannot produce energy, and the core contracts and grows hotter. The shells around the core burn outward, fusing lighter elements into heavier elements and leaving behind more iron, which further increases the mass of the core. When the mass of the iron core exceeds a limit of about 1.3 to 2 solar masses, it must collapse.

As the core begins to collapse, two processes can make it contract even faster. Heavy nuclei in the core capture high-energy electrons, removing thermal energy from the gas. This robs the gas of some of the pressure it needs to support the crushing weight of the outer layers. Also, temperatures are so high that many photons have gamma-ray wavelengths and are capable of breaking more massive nuclei into less massive nuclei. In the process, the gamma rays are absorbed, which robs the gas of energy and allows the core to collapse even faster.

Although a massive star may live for millions of years, its iron core—about 500 km in diameter—collapses in only a few thousandths of a second, triggering a star-destroying explosion.

The Supernova Deaths of Massive Stars

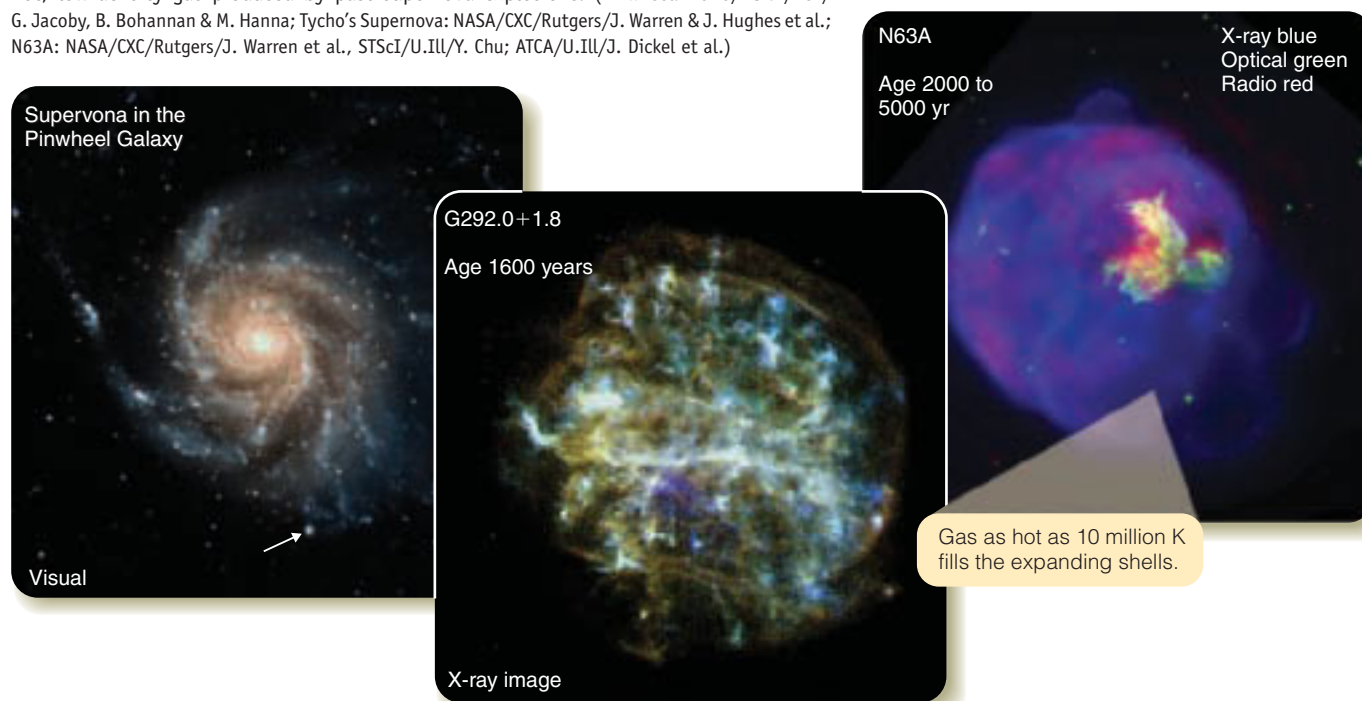
In the 1930s, astronomers realized that some of the novae that had been seen in the sky were much more luminous and longer lasting than the others, and they dubbed such an object a **supernova** (plural, **supernovae**). Modern astronomers understand that a supernova is caused by the violent, explosive death of a massive star.

A few novae appear in the sky each year, but supernovae are so rare that only one or two supernovae are observed each century in our galaxy. Astronomers know that supernovae occur because they occasionally are seen to flare in other galaxies, and because telescopes reveal the shattered remains of these titanic explosions (■ Figure 13-11). Modern theory predicts that the collapse of the core in a massive star can eject the outer layers of the star to produce one of the most common kinds of supernova explosions. You will learn about another kind of supernova explosion later in this section.

A supernova explosion is rare, remote, rapid, and violent. It is an event that is extremely difficult to study directly, which is why astronomers have used powerful mathematical techniques and high-speed supercomputers to model the inside of a star as it explodes. Such models allow astronomers, in a sense, to experiment on supernovae as if the stars were in a laboratory.

■ Figure 13-11

Supernova explosions are rare in any one galaxy, but each year astronomers see a few erupt in other galaxies. In our own galaxy, astronomers find expanding shells filled with hot, low-density gas produced by past supernova explosions. (Pinwheel: NOAO/AURA/NSF/G. Jacoby, B. Bohannan & M. Hanna; Tycho's Supernova: NASA/CXC/Rutgers/J. Warren & J. Hughes et al.; N63A: NASA/CXC/Rutgers/J. Warren et al., STScI/U.Ill/Y. Chu; ATCA/U.Ill/J. Dickel et al.)



Those models reveal that the key to a supernova explosion is the collapse of the iron core. This collapse allows the rest of the star's interior to fall inward, creating a tremendous "traffic jam" as all the nuclei fall toward the center. It is as if all the residents of Indiana suddenly tried to drive their cars as fast as possible into the center of Indianapolis. There would be a tremendous traffic jam downtown, and as more cars rushed in, the traffic jam would spread outward into the suburbs. Similarly, as the inner core of the star falls inward, a shock wave (a traffic jam) develops and begins to move outward. Such a shock wave was first thought to be the cause of the supernova explosion. Computer models revealed, however, that the shock wave spreading outward through the collapsing star stalls within a few hundredths of a second. Matter falling inward smothers the shock wave and pushes it back into the star. Those computer models wouldn't successfully explode.

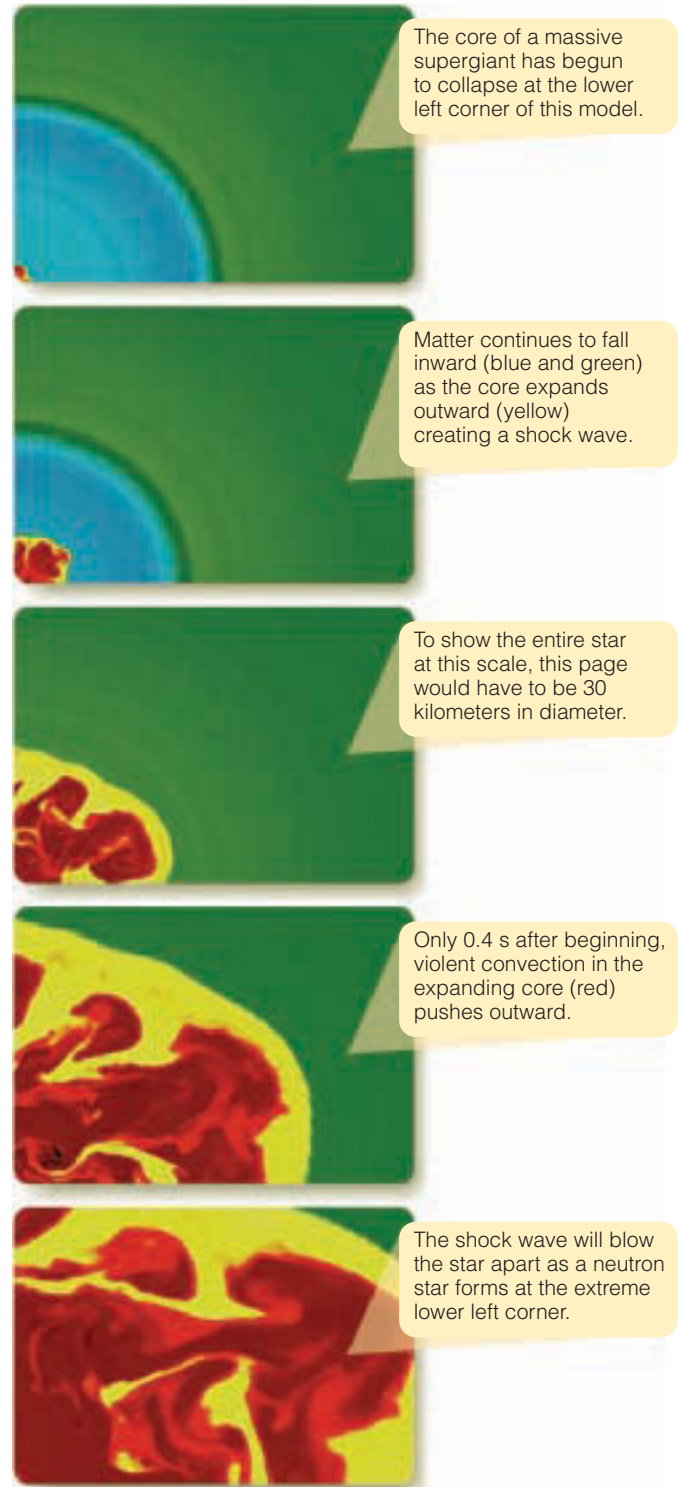
Then why does the star explode? Theory predicts that 99 percent of the energy released as the core collapses appears in the form of the subatomic particles known as neutrinos (see Chapter 8). In the sun, neutrinos zip outward unimpeded by the gas of the solar layers, but in a collapsing star the gas is billions of times denser than the gas in the sun, nearly as dense as an atomic nucleus. That gas is nearly opaque to neutrinos, and they are partially absorbed by the gas. Not only does the tremendous burst of neutrinos remove energy from the core and allow it to collapse even faster, but when the neutrinos are absorbed outside the core they heat those layers. For some years, astronomers thought that these neutrinos could spread energy across the shock wave and, within a quarter of second or so, reaccelerate the stalled shock wave. The computer models, however, still refused to explode.

The final ingredient that the models needed was turbulent convection. When the collapse begins, the very center of the star forms a highly dense core, the beginnings of a neutron star, and the in-falling material bounces off that core. As the temperature shoots up, the bouncing material produces highly turbulent convection currents that give the stalled shock wave an outward boost (■ Figure 13-12). Within a second or so, the shock wave begins to push outward again, and after just a few hours it bursts out through the surface, blasting the star apart in a supernova explosion.

Of course, supernova explosions occur in silence. Science fiction movies and television have led to the **Common Misconception** that explosions in space are accompanied by deeply satisfying sonic booms. But space is nearly a vacuum, so there can be no sound. Some of the most violent events in the universe make no noise at all.

The supernova visible from Earth is the brightening of the star as its outer layers are blasted outward. As the months pass, the cloud of gas expands, thins, and begins to fade. The way it fades can tell astronomers about the death throes of the star. Essentially all of the iron in the core of the star is destroyed when the core collapses, but the violence in the outer layers during the explosion can produce densities and temperatures high enough to trigger nuclear fusion reactions that produce as much as half a solar mass

The Exploding Core of a Supernova



■ **Figure 13-12**

As the iron core of a massive star begins to collapse, intensely hot gas triggers violent convection. Even as the outer parts of the core continue to fall inward, the turbulence blasts outward and reaches the surface of the star within hours, creating a supernova eruption. This diagram is based on mathematical models and shows only the exploding core of the star. (Courtesy Adam Burrows, John Hayes and Bruce Fryxell)

of radioactive nickel-56. The nickel gradually decays to form radioactive cobalt, which decays to form normal iron. The rate at which the supernova fades matches the rate at which these radioactive elements decay. Thus the destruction of iron in the core of the star is matched by the production of iron through nuclear fusion and eventual radioactive decay in the expanding outer layers.

The presence of nuclear fusion in the outer layers of supernovae testifies to the violence of the explosion. A typical supernova is equivalent to the explosion of 10^{28} megatons of TNT—about 5 million solar masses of high explosive.

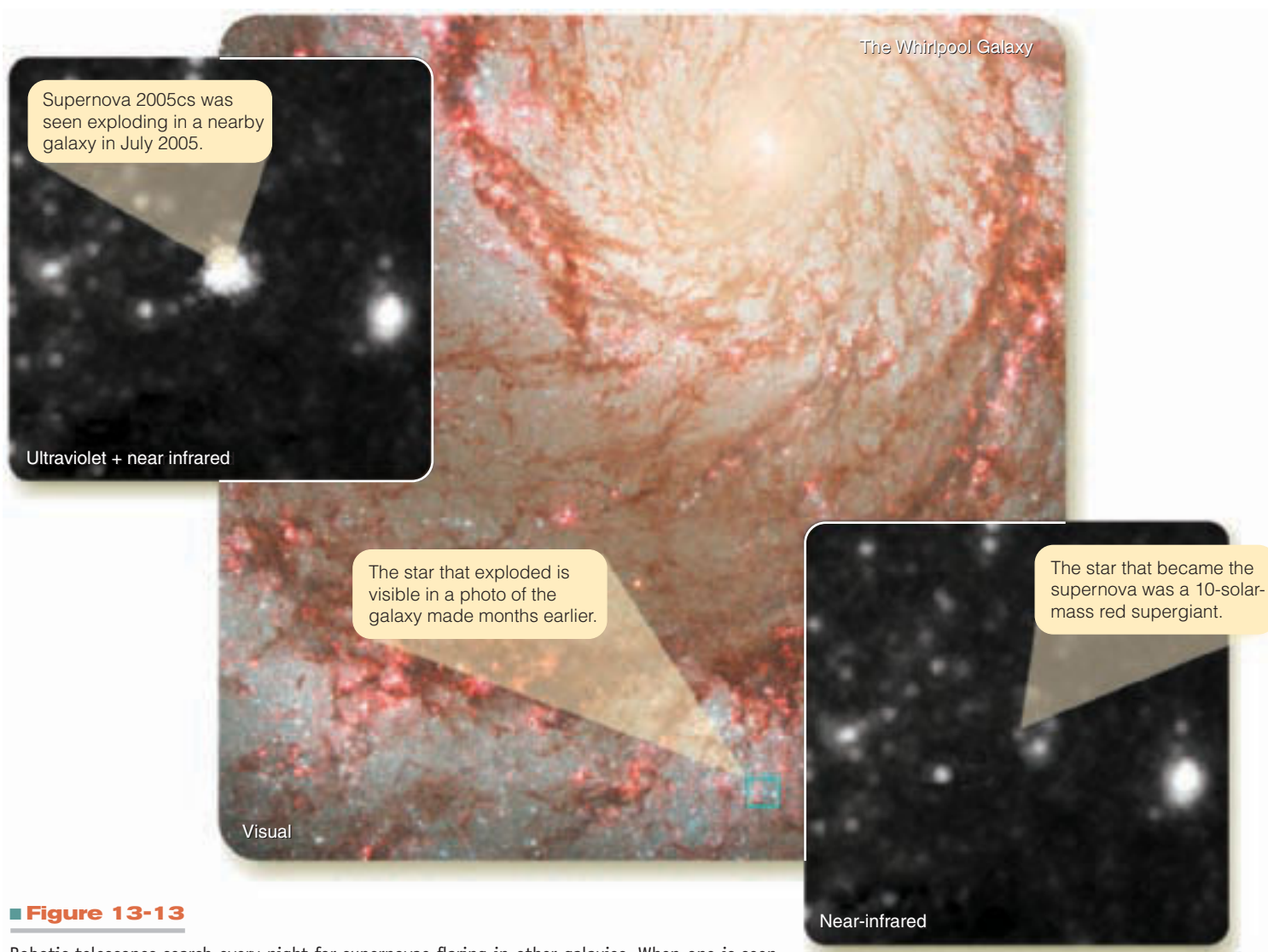
Supernovae may seem powerful and remote, but you have a personal connection with the deaths of stars. All of the atoms in your body heavier than helium but lighter than iron were cooked up in red giant stars. Some were made in medium-mass stars and

expelled in planetary nebula. Even more were made inside massive stars and blasted into space in supernova explosions. Short-lived nuclear fusion reactions taking place during supernova explosions created iron and rare elements heavier than iron such as the iodine in your thyroid gland, and platinum, gold, and silver. You are made of atoms that were created by the stars, and your jewelry comes from star explosions.

Collapsing massive stars can trigger one kind of cosmic violence, but astronomers have observed more than one kind of supernova.

Types of Supernovae

Supernovae are rare, and only a few have been seen in our galaxy, but astronomers have been able to observe supernovae occurring in other galaxies (■ Figure 13-13). From data accumulated over



■ **Figure 13-13**

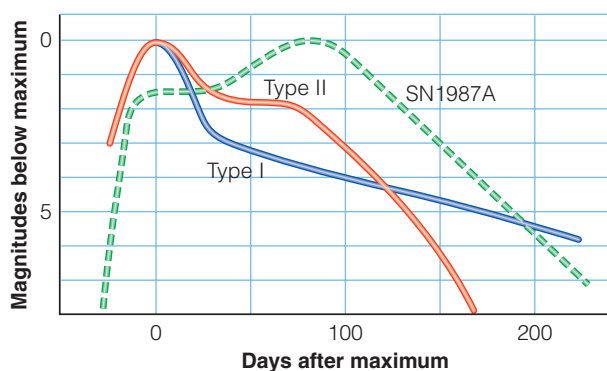
Robotic telescopes search every night for supernovae flaring in other galaxies. When one is seen, astronomers can obtain spectra and record the supernova's rise in brightness and its decline to study the physics of exploding stars. If a supernova is seen in a nearby galaxy, it is sometimes possible to identify the star in earlier photos. (NASA, ESA, W. Li and S. Filippenko, Berkeley, S. Beckwith, STScI, and The Hubble Heritage Team, STScI/AURA)

decades, astronomers have noticed that there are two main types. **Type I supernovae** have spectra that contain no hydrogen lines. They reach a maximum brightness about 4 billion times more luminous than the sun and then decline rapidly at first and then more slowly. **Type II supernovae** have spectra containing hydrogen lines. They reach a maximum brightness up to about 0.6 billion times more luminous than the sun (less than type I supernovae), decline to a temporary standstill, and then fade rapidly. The light curves in ■ Figure 13-14 summarize the behavior of the two types of supernovae.

The evidence is clear that type II supernovae occur when a massive star develops an iron core and collapses. Such supernovae occur in or near regions of active star formation. These are the regions where you would expect to find massive stars. Also, the spectra of type II supernovae contain hydrogen lines, as you would expect from the explosion of a massive star that contains large amounts of hydrogen in its outer layers.

Type I supernovae show no hydrogen in their spectra, which means they can't be caused by the deaths of typical massive stars. In fact, there are two kinds of type I supernovae, and they have dramatically different causes. Both involve binary stars.

A **type Ia supernova** occurs when a white dwarf gaining mass in a binary star system exceeds the Chandrasekhar limit and collapses. The collapse of a white dwarf is different from the collapse of a massive star because the white dwarf contains usable nuclear fuel—mainly carbon. As the collapse begins, the temperature shoots up, but the gas cannot halt the collapse because it is degenerate, and the pressure–temperature thermostat is turned off in the core. Even as carbon fusion begins, the increased temperature cannot increase the pressure and make the gas expand and slow the reactions. The lack of a thermostat



■ **Figure 13-14**

Type I supernovae decline rapidly at first and then more slowly, but type II supernovae pause for about 100 days before beginning a steep decline. Supernova 1987A was odd in that it did not rise directly to maximum brightness. These light curves have been adjusted to the same maximum brightness. Generally, type II supernovae are about two magnitudes fainter than type I.

makes the collapsing white dwarf into a bomb. The carbon–oxygen core fuses suddenly in violent nuclear reactions called **carbon deflagration** and produces a wide range of heavier nuclei. The word *deflagration* means to be totally destroyed by fire, in this case by nuclear fusion. In a flicker of a stellar lifetime, the white dwarf is consumed, with the resulting heavy nuclei and outer layers blasted away in a violent explosion that at its brightest is three to six times more luminous than a type II supernova. The white dwarf is destroyed with nothing left behind but an expanding cloud of hot gas. Of course, you would see no hydrogen lines in the spectrum of a type Ia supernova because white dwarfs contain at most only a little hydrogen in their outer layers.

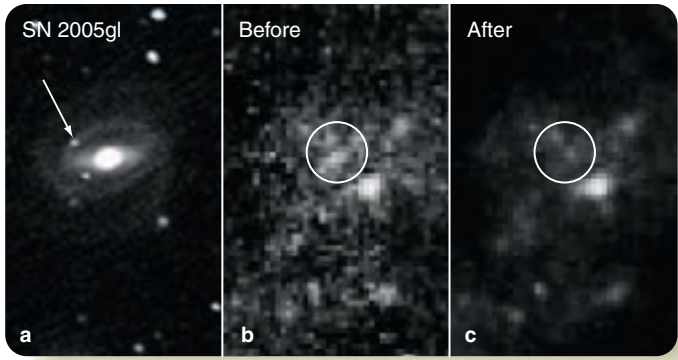
You might wonder why a white dwarf gaining mass doesn't erupt in a nova explosion and blast the mass away. Mathematical models show that the nova eruption does not necessarily blow away all of the mass the white dwarf has gained. So it is possible for a white dwarf to gain mass, erupt a number of times as a nova, and eventually become so massive it collapses in a type Ia supernova explosion.

The less common **type Ib supernovae** are thought to occur when a massive star in a binary system loses its hydrogen-rich outer layers to its companion star. The remains of the massive star continue to evolve, develop an iron core, and collapse, producing a supernova explosion that lacks hydrogen lines in the spectrum. Some astronomers have referred to these as “peeled” supernovae, meaning that the massive star has had its hydrogen-rich outer layers peeled away by its binary companion.

To summarize, a type II supernova is caused by the collapse of a massive star. A type Ia is caused by the collapse of a white dwarf. A type Ib is caused by the collapse of a massive star that has lost its outer envelope of hydrogen. The distinction is evident even in the location of these supernovae. Type II and type Ib supernovae are caused by the collapse of massive stars, which don't live very long. Those types of supernovae are seen near regions of active star formation. In contrast, type Ia supernovae are caused by the collapse of white dwarfs, and it takes a long time for the evolution of stars to produce white dwarfs. That's why type Ia supernovae are seen in regions where star formation took place long ago.

There may be other types of supernovae caused by other processes that can make a massive star explode. For example, SN 2005gl has been identified with a very luminous, hot supergiant, and astronomers did not expect such a star to explode (■ Figure 13-15). That supernova remains a puzzle. Supernovae are so rare, Earth's astronomers may not have seen every type that can occur.

Much of what you have learned so far about supernovae has been based on theory, so it is time to compare theory with observations of real supernova explosions. These frequent reality checks are a distinguishing characteristic of science.



Visual-wavelength images

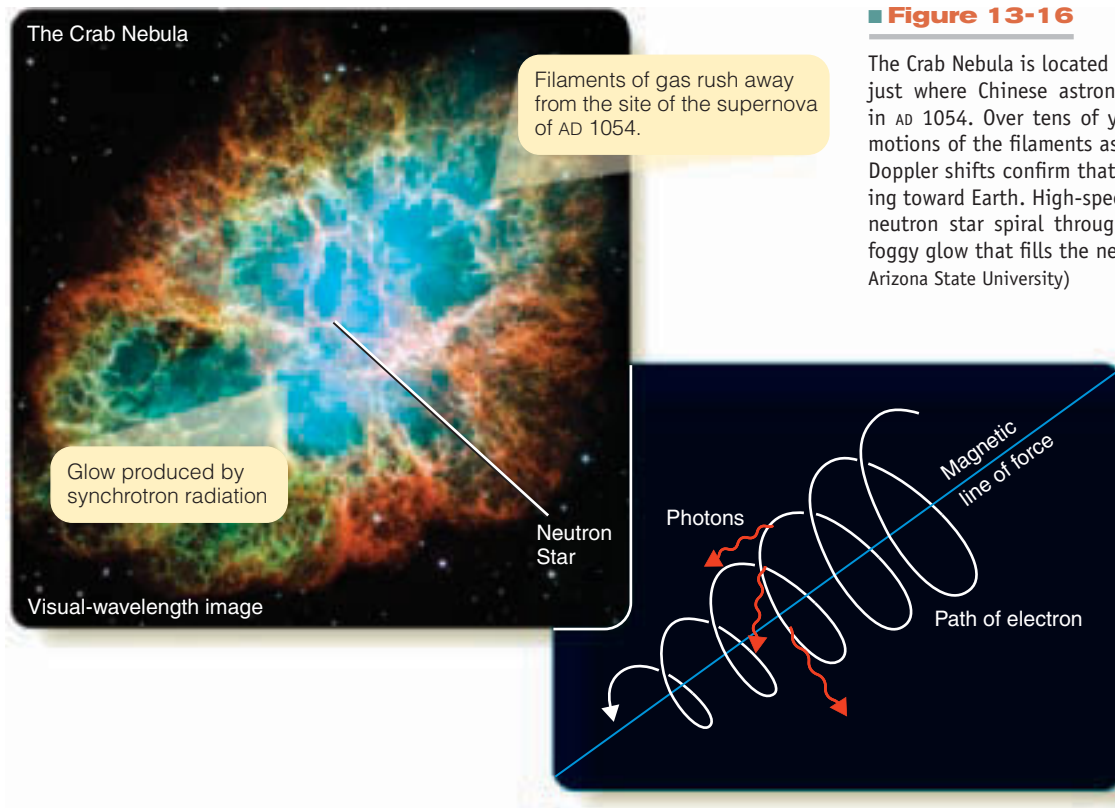
■ **Figure 13-15**

(a) SN 2005gl was seen erupting in the galaxy NGC 266, 215 million light-years from Earth. (b) In a 1997 image, the star is visible as a highly luminous blue supergiant, a class of star not expected to explode as a supernova. (c) In a 2007 image recorded after the explosion had faded away, the star is gone. (a. Puckett Observatory; b. and c. NASA, ESA, A. Gal-Yam, Weizmann Inst. of Science, Israel)

Observations of Supernovae

In AD 1054, Chinese astronomers saw a “guest star” appear in the constellation now known as Taurus, the bull. The star quickly became so bright it was visible in the daytime. After a month’s time, it slowly faded, taking almost two years to vanish from sight. When modern astronomers turned their telescopes to the location of the guest star, they found a cloud of gas about 1.4 pc in radius, expanding at 1400 km/s. Projecting the expansion back in time, they concluded that it must have begun about nine centuries ago, just when the Taurus guest star made its visit. From this and other evidence, astronomers conclude that the nebula, now called the Crab Nebula because of its shape (■ Figure 13-16), marks the site of the 1054 supernova.

The glowing filaments of the Crab Nebula appear to be excited gas flung outward by the explosion, but the hazy glow in the inner nebula is something else. Radio observations show that the gas in the nebula is emitting **synchrotron radiation**—electromagnetic energy radiated by high-speed electrons spiraling through a magnetic field. Electrons moving at different velocities radiate at different wavelengths, so synchrotron radiation is spread over a wide range of wavelengths. The foggy glow in the Crab Nebula is synchrotron radiation at the relatively short wavelengths of visible light, which means the electrons must be traveling at tremendous speeds. In the nine centuries since the Crab supernova explosion, the electrons should have radiated their energy away and slowed down. Evidently they



■ **Figure 13-16**

The Crab Nebula is located in the constellation Taurus the Bull, just where Chinese astronomers saw a brilliant “guest star” in AD 1054. Over tens of years, astronomers can measure the motions of the filaments as they expand away from the center. Doppler shifts confirm that the near side of the nebula is moving toward Earth. High-speed electrons produced by the central neutron star spiral through magnetic fields and produce the foggy glow that fills the nebula. (NASA, ESA, J. Hester and A. Loll, Arizona State University)

have not, so there must be an energy source in the Crab Nebula that is producing very-high-speed electrons. You will use this clue in the next chapter and discover a neutron star at the center of the Crab Nebula.

In contrast, Kepler's supernova of 1604 left nothing behind but a cloud of gas and dust. Astronomers analyzing the chemical content of the cloud conclude the explosion was a type Ia supernova, so it would not have formed a neutron star or black hole. In fact, a team of astronomers has found the companion star that spilled mass onto the white dwarf. When the white dwarf exploded, the companion star was suddenly freed and its orbital velocity carried it away into space. It is seen today rushing away from the site of the explosion.

A supernova fades to obscurity in a year or two, but it produces an expanding shell of gas, originally expelled at 10,000 to 20,000 km/s, called a **supernova remnant**. As the supernova remnant cools, some of the gas condenses to form dust, and that makes supernovae one of the biggest sources of the dust in the interstellar medium. As you learned earlier, there are several processes that cause a supernova remnant to remain visible long after the explosion itself is over. Another such process is collision of the expanding shell of gas and dust with the surrounding interstellar medium that can sweep up even more gas and excite it to produce a glowing nebula.

Supernova remnants look quite delicate and do not survive very long—a few tens of thousands of years—before they gradually mix with the interstellar medium and vanish. The Crab Nebula is a young remnant, only about 950 years old, and it isn't very large, only a few parsecs in diameter. Older remnants can be larger. Some supernova remnants are detectable only at radio and X-ray wavelengths. They have become too tenuous to emit much visible light, but the collision of the expanding hot gas with the interstellar medium can generate radio and X-ray radiation and allows astronomers to create images of them at these non-visible wavelengths. In general, supernova remnants are low-density shells of gas expanding into the interstellar medium (■ Figure 13-17). You saw in Chapter 11 that the compression of the interstellar medium by expanding supernova remnants can trigger star formation.

The supernova remnant Cassiopeia A (Cas A) is only about 300 years old, although there is no record of a supernova being seen at that location. The Chandra X-ray Observatory has recorded a series of X-ray images beginning in 2001 (Figure 13-17), and they allow astronomers to see the gas cloud expanding. Detailed studies reveal jets rich in silicon and iron. Infrared images made by the Spitzer Space Telescope combined with ground-based observations have allowed astronomers to create a three-dimensional model of the remnant. These studies show that the outer layers of the star were ejected in a spherical shell, but parts of the stars' interior were ejected in a flattened disk. Theoretical models have not yet explained that geometry.

The Crab Nebula is important because it is a young supernova remnant linked to a supernova explosion that was actually seen to occur. Supernovae are rare, and only a few have been visible to the naked eye during all of recorded history. Arab astronomers recorded one in 1006, and the Chinese saw the Crab supernova in 1054. The guest stars of 185, 386, 393, and 1181 may also have been supernovae. European astronomers observed two—one in 1572 (Tycho's supernova) and one in 1604 (Kepler's supernova). Most supernovae are discovered in distant galaxies, but those are faint and difficult to study.

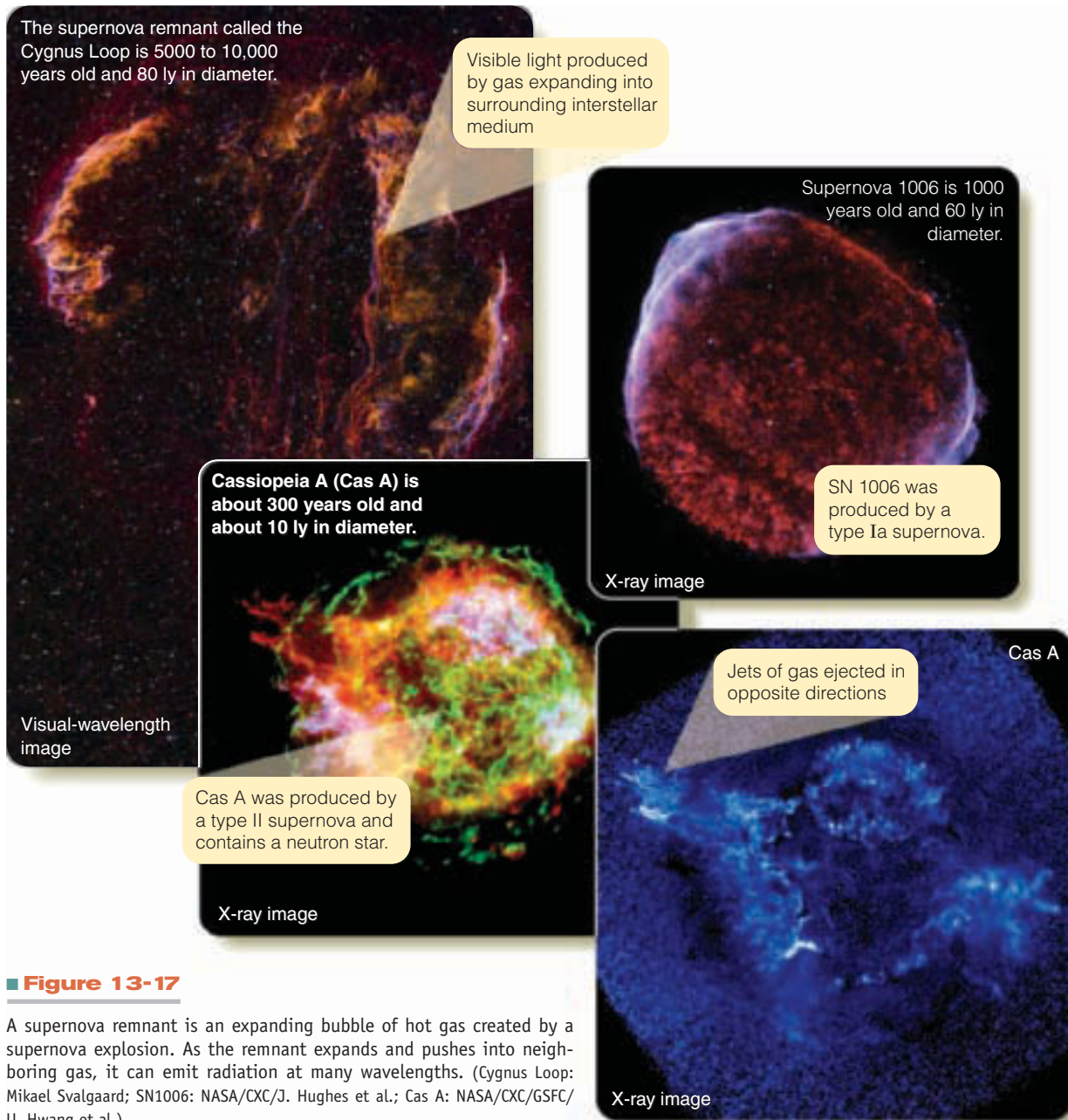
The Supernova of 1987

For the 383 years following Kepler's supernova in 1604, no naked-eye supernova was seen. Then, in late February 1987, the news raced around the world: Astronomers in Chile had discovered a naked-eye supernova in the Large Magellanic Cloud, a small galaxy very near our Milky Way Galaxy (■ Figure 13-18). Because the supernova was only 20 degrees from the south celestial pole, it could be studied only from southern latitudes. It was named SN 1987A to denote the first supernova discovered in 1987.

The hydrogen-rich spectrum suggested that the supernova was a type II, caused by the collapse of the core of a massive star. As the months passed, however, the light curve proved to be odd in that it paused for a few weeks before rising to its final maximum (see Figure 13-14). From photographs of the area made some years before, astronomers were able to determine that the star that exploded, cataloged as Sanduleak $-69^{\circ}202$, was not the expected red supergiant but rather a hot, blue supergiant of about 20 solar masses and 50 solar radii, not extreme for a supergiant. Theorists now believe that the star was chemically poor in elements heavier than helium and had consequently contracted and heated up after a phase as a cool, red supergiant, during which it had lost mass into space. The brightening of the supernova may have gone through a pause because much of the energy of the explosion went into blowing apart the smaller, denser-than-usual star and making it expand.

The brightening of the expanding gases after the first few weeks seems to have been caused by the decay of radioactive nickel into cobalt, which emitted gamma rays that heated the expanding shell of gas and made it brighter. About 0.07 solar mass of nickel was produced, about 20,000 times the mass of Earth.

The cobalt atoms are also unstable, but they decay more slowly, so it was not until some time later, after much of the nickel had decayed, that the decay of cobalt into iron began providing energy to keep the expanding gas hot and luminous. Although these processes had been predicted, they were clearly observed in SN 1987A. Gamma rays from the decay of cobalt to iron were detected above Earth's atmosphere, and cobalt and iron are clearly visible in the infrared spectra of the supernova.



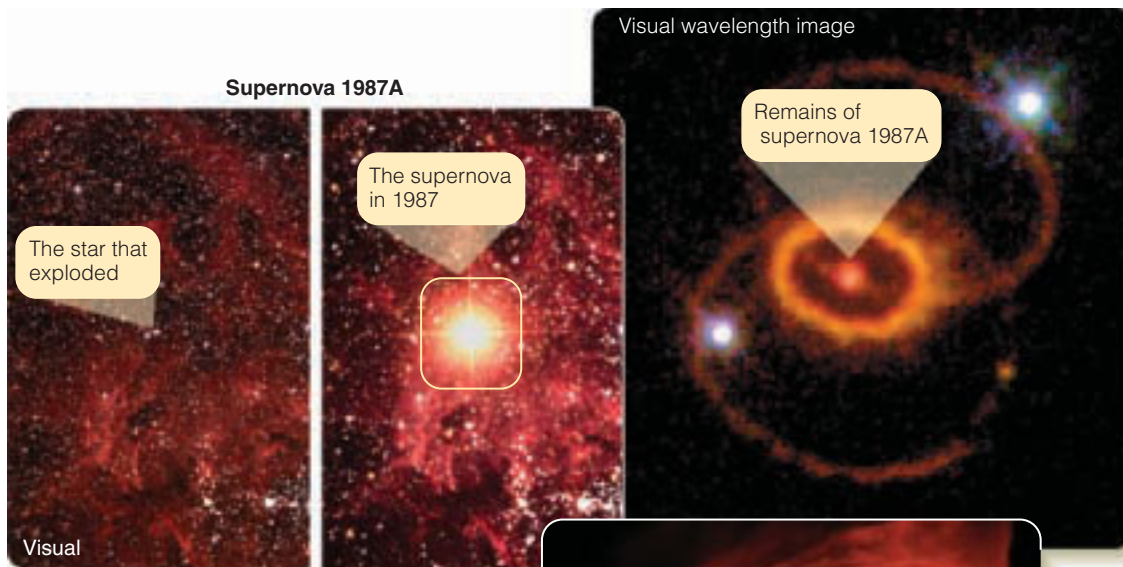
■ **Figure 13-17**

A supernova remnant is an expanding bubble of hot gas created by a supernova explosion. As the remnant expands and pushes into neighboring gas, it can emit radiation at many wavelengths. (Cygnus Loop: Mikael Svalgaard; SN1006: NASA/CXC/J. Hughes et al.; Cas A: NASA/CXC/GSFC/U. Hwang et al.)

As the expanding gases dimmed, photographs revealed bright rings of gas (look again at Figure 13-18). Comparison with mathematical models shows that the rings were produced by two stellar winds. When the star was a red supergiant, it expelled a slow stellar wind. Later, when it became a blue supergiant, it expelled a fast stellar wind. The interaction of these two winds, shaped by a magnetic field and illuminated by the supernova explosion, produces the rings. Compare this with the rings seen in some of the planetary nebulae shown on page 261.

Two independent observations confirm that SN 1987A probably gave birth to a neutron star. As you learned earlier, theory predicts that as a massive star's core collapses into a

neutron star it should liberate a tremendous blast of neutrinos that leave the star hours before the shock wave from the interior blows the star apart. Two independent neutrino detectors, one in Ohio and one in Japan, recorded a burst of neutrinos passing through Earth at 2:35:41 AM EST on February 23, 1987, a few hours before the supernova was seen. The data show that the neutrinos rushed toward Earth from the direction of the supernovae. The detectors caught only 19 neutrinos during a 12-second interval, but recall that neutrinos hardly ever react with normal matter. Even though only 19 were detected, the full flood of neutrinos must have been immense. Within a few seconds of that moment, roughly 20 trillion neutrinos passed



■ **Figure 13-18**

The star that exploded as supernova 1987A was about 20 times the mass of the sun. The interaction of matter previously lost by the star, gas recently ejected, and the burst of light from the explosion have produced rings around the central glow as shown in the artist's impression. A shock wave from the explosion is now expanding into a 1 ly diameter ring of gas ejected roughly 20,000 years before the explosion. As that ring is excited, it will light up the region and reveal how the star shed mass before it collapsed. (Starfields: AATB; Rings: Christopher Burrows, ESA/STScI, NASA; Artwork: NASA, ESA, STScI and Don Dixon)

harmlessly through each human body on Earth. The detection of the neutrino blast confirms that the collapsing core gave birth to a neutron star.

Over time the expanding gas shell of the supernova will continue to thin and cool, and eventually astronomers on Earth will be able to peer inside and see what is left of Sanduleak –69°202. Will they see the expected neutron star, or will theories need further revision? For the first time in almost 400 years, astronomers can observe a bright supernova to test their theories.

Local Supernovae and Life on Earth

Although supernovae are rare events, they are very powerful and could affect life on planets orbiting nearby stars. In fact, supernovae explosions long ago may have affected Earth's climate and the evolution of life.

If a supernova were to occur within a few light years of Earth, the human race would have to abandon the surface and live below ground for at least a few decades. The burst of gamma rays and high-energy particles from the supernova explosion could kill many life forms and cause serious genetic damage in others. The

only way to avoid this radiation would be to move the population into tunnels below Earth's surface. Of course, if a supernova did occur, there would not be time to dig enough tunnels.

Even if you could survive in tunnels long enough for the radioactivity on Earth's surface to subside, you might not like Earth when you emerged. Genetic mutation induced by radioactivity might alter plant and animal life so seriously that the human population could not be supported. After all, humans depend almost totally on grass for food. The basic human foods—milk, butter, eggs, wheat, tomatoes, lettuce, and meat (Big Macs, in other words)—are grass and similar vegetation processed into different forms. Seafood is merely processed ocean plankton and plant life, which might also be altered or damaged by a local supernova explosion.

Even if a supernova were 25 to 100 ly away, it could seriously damage Earth's ozone layer and alter the climate dramatically. Local supernovae have been suggested as a possible cause of occasional climate changes and extinctions in Earth's past. It is almost certain that, as the sun moves through space, supernovae explode near enough to affect Earth every few hundred million years. A close call could trigger an extinction.

Is there any evidence that supernovae really affect Earth? In 1979, scientists studying Antarctic ice cores containing very old ice noticed that ice from the years 1181, 1320, 1572, and 1604 contains high abundances of nitrates. Bright supernovae were seen in the years 1181, 1572, and 1604. Ultraviolet radiation from those supernovae might have altered Earth's upper atmosphere and produced acid rain that was recorded in the ice as nitrates. But what of the ice from 1320? In 1999, X-ray astronomers noticed a supernova remnant in the southern sky. When they calculated its age, they found the supernova should have occurred about 1320. It isn't clear why there is no historical record of this supernova or why the nitrates appear in Antarctic ice cores but not in Greenland ice cores. In any case, this evidence may be a warning that even distant supernova explosions can affect Earth in subtle ways.

A study of cores from the seafloor has revealed a deposit of the isotope iron-60 in a layer that was laid down at the time of the Pliocene-Pleistocene extinction about 2 million years ago. Iron-60 is produced in supernova explosions and has a half-life of only 1.5 million years. To reach Earth before it decayed, this iron must have been produced in a supernova explosion no more than 100 ly away. Some scientists wonder if the Pliocene-Pleistocene extinction was caused by a nearby supernova explosion.

Earth seems to be fairly safe at the moment. No star within 500 ly is known to be a massive giant capable of exploding as a

type II supernova. Type Ia supernovae, however, are caused by collapsing white dwarfs, and white dwarfs are both common and hard to locate. There is no way to be sure that a white dwarf teetering on the edge of the Chandrasekhar limit does not lurk near us in space. You can take comfort, however, in the rarity of supernova explosions, which seem to occur within our view only a few times per millenium. Earth faces greater dangers from human ignorance than from exploding stars.

SCIENTIFIC ARGUMENT

Why does a type II supernova explode?

For this argument you need to review theory rather than evidence. A type II supernova occurs when a massive star reaches the end of its usable fuel and develops an iron core. The iron is the final ash produced by nuclear fusion, and it cannot fuse because iron is the most tightly bound nucleus. When energy generation begins to decrease, the star contracts, but because iron can't ignite there is no new energy source to stop the contraction. In seconds, the core of the star falls inward, and a shock wave moves outward. Aided by a flood of neutrinos and sudden convective turbulence, the shock wave blasts the star apart; seen from Earth, it brightens as its surface gases expand into space.

Now revise your argument to consider evidence. **What evidence can you cite to support the theory that the core of a type II supernova can form a neutron star?**

What Are We? Stardust

You are made of atoms that were cooked up inside stars. Gravity draws matter together to make stars, and although nuclear fusion delays gravity's final victory, stars must eventually die. That process of star life and star death manufactures atoms heavier than helium and spreads them back into the interstellar medium, where they can become part of the gas clouds that form new stars. All of the atoms in your body except for the hydrogen were made inside stars.

Some of your atoms, such as the carbon, were cooked up in the cores of medium-mass stars like the sun and were puffed out into space when those stars died and produced planetary nebulae. Some of your atoms, such as the calcium in your bones, were made inside massive stars and were blown out into space during a type II supernova explosion. Many of the iron atoms in your blood were made by the sudden fusing of carbon when white dwarfs

collapsed in type Ia supernova explosions. In fact, a few of your heavier atoms, such as iodine in your thyroid gland, selenium in your nerve cells, and gold in your class ring, were produced in the raging violence of supernova explosions.

You are made of atoms scattered into space long ago by the violent deaths of stars. What are we? We are stardust.

Study and Review

Summary

- ▶ Red dwarfs less massive than about 0.4 solar mass are completely mixed internally by convection. They cannot ignite a hydrogen fusion shell, so they cannot become giant stars. Because they have little weight to support and can fuse nearly all of their hydrogen fuel, they will remain on the main sequence for many times the present age of the universe and then contract to become white dwarfs. The universe is not old enough for any white dwarfs to have formed in this way.
- ▶ Medium-mass stars between about 0.4 and 4 solar masses, including the sun, become cool giants and fuse helium but cannot fuse carbon. While they are giants, they lose mass into space, a process that is helped by **thermal pulses (p. 257)** in their helium fusion shells. Finally such stars collapse to become white dwarfs.
- ▶ If the collapsed star becomes hot enough, it can ionize the gas it has ejected first as a slow wind and later as a fast wind to produce a **planetary nebula (p. 257)**.
- ▶ White dwarfs are the remains of sun-like stars that have collapsed until their gas becomes degenerate. Because white dwarfs are small, dense, and generate no fusion energy, they are sometimes called **compact objects (p. 259)**, along with neutron stars and black holes. Because white dwarfs have no nuclear fuels they will slowly cool off and eventually become **black dwarfs (p. 259)**. The universe is not old enough yet for any black dwarfs to have formed.
- ▶ A white dwarf cannot support its own weight by its degenerate pressure if its mass is greater than the **Chandrasekhar limit (p. 262)** of 1.4 solar masses. Medium-mass stars up to about 8 solar masses can lose enough mass during their lives to shrink under the Chandrasekhar limit and die as white dwarfs. This explains the large number of white dwarfs found in space.
- ▶ Two stars orbiting each other control two regions of space called **Roche lobes (p. 263)**. The surface of these lobes is called the **Roche surface (p. 263)**. The **Lagrangian points (p. 263)** mark places of stability in the system, and mass can flow from one star to the other through the **inner Lagrangian point (p. 263)**.
- ▶ Close binary stars evolve in complex ways because they can transfer mass from one star to the other. This explains why some binary systems contain a main-sequence star more massive than its giant companion—the Algol paradox.
- ▶ Mass is transferred from an evolving star through an **accretion disk (p. 264)** around the receiving star. Accretion disks can become hot enough to emit light and even X-rays.
- ▶ Mass transferred onto the surface of a white dwarf can build up a layer of fuel that fuses suddenly in a **nova (p. 264)** explosion. A white dwarf can erupt repeatedly so long as mass transfer continues to form new layers of fuel.
- ▶ Stars more massive than about 8 solar masses cannot lose mass fast enough to reduce their mass low enough to die by ejecting a planetary nebula and collapsing into a white dwarf. Such massive stars must die more violent deaths.
- ▶ The end of Earth will come in about 5 billion years when the sun expands, goes through two red giant phases, and engulfs Earth. Most of the atoms now on Earth's surface will be blown outward to rejoin the interstellar medium. If the sun collapses quickly enough into a hot white dwarf, the gas it has expelled will be excited to glow as a planetary nebula.
- ▶ The massive stars on the upper main sequence fuse nuclear fuels up to iron but cannot generate further nuclear energy because iron is the most tightly bound of all atomic nuclei. When a massive star forms

an iron core, the core collapses and triggers a **supernova (p. 268)** explosion known as a **type II supernova (p. 271)**.

- ▶ A **type I supernova (p. 271)** has no hydrogen lines in its spectra. A **type Ia supernova (p. 271)** can occur when mass transferred onto a white dwarf pushes it over the Chandrasekhar limit and the white dwarf collapses suddenly, fusing all of its carbon at once in a burst of **carbon deflagration (p. 271)**. Type Ia supernovae have no hydrogen lines because white dwarfs contain very little hydrogen.
- ▶ A **type Ib supernova (p. 271)** occurs when a massive star in a binary system loses its outer layers of hydrogen due to mass transfer. Later its iron core can collapse, and it can explode as a type Ib supernova, which lacks hydrogen lines.
- ▶ Many atoms heavier than iron are produced inside supergiant stars and then blown into space by supernova explosions. Many other heavy atoms are produced by fusion reactions that take place during supernova explosions.
- ▶ **Supernova remnants (p. 273)** are the expanding shells of gas ejected by supernova explosions. They are filled with hot gas. The Crab Nebula is a supernova remnant formed by the supernova of AD 1054.
- ▶ The hazy glow in the Crab Nebula is produced by **synchrotron radiation (p. 272)** and is evidence that some energy source remains in the nebula. Observations have found a neutron star there.
- ▶ The supernova of 1987 is believed to have been produced by a peculiar type II supernova explosion. Neutrinos from the explosion were detected on Earth and are evidence that the star's iron core collapsed, presumably forming a neutron star, although it has not yet been detected.
- ▶ Supernova explosions near Earth could alter the ozone layer, change Earth's climate, and produce some of the extinctions that are seen in the fossil record.

Review Questions

1. Why can't the lowest-mass stars become giants?
2. Presumably, all the white dwarfs in our galaxy were produced by sun-like stars of medium mass. Why couldn't any of these white dwarfs have been produced by the deaths of the lowest-mass stars?
3. What evidence can you cite that stars can lose mass?
4. What kind of spectrum does the gas in a planetary nebula produce? Where does it get the energy to radiate?
5. The coolest stars at the center of planetary nebulae are about 25,000 K. Why don't astronomers see planetary nebulae containing cooler central stars? (*Hint:* What kind of photons excite the gas in a planetary nebula?)
6. As white dwarfs cool, they move toward the lower right in the H-R diagram (Figure 9-9 and page 261), maintaining constant radius. Why don't they contract as they cool?
7. All white dwarfs are about the same mass. Why?
8. Why have no white dwarfs cooled to form black dwarfs in our galaxy?
9. What happens to a star in a close binary system when it becomes a giant?
10. Why do novae repeat while supernovae do not?
11. Why can't stars generate energy from iron fusion?
12. How could you use spectra to tell the difference between a type I supernova and a type II supernova? Why does this difference arise?
13. What processes produce type I and type II supernovae?
14. Why do supernova remnants emit X rays?
15. **How Do We Know?** How could you trace the ultimate causes of supernova explosions back to the behavior of subatomic particles?

Discussion Questions

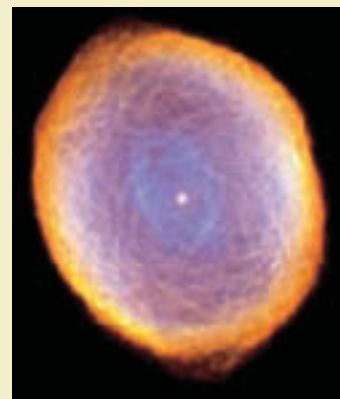
1. How certain can you be that the sun will never explode as a supernova? What does it mean when a scientist uses the word *certainty*?
2. If humans could live for millions of years, they might notice stars that had exploded repeatedly as novae finally being destroyed in supernova explosions. What could account for this?

Problems

1. Use the formula in Chapter 12 to compute the life expectancy of a 0.4-solar-mass star. Why might this be an underestimate if the star is fully mixed?
2. The Ring Nebula in Lyra is a planetary nebula with an angular diameter of 76 arc seconds and a distance of 5000 ly. What is its linear diameter? (*Hint*: Use the small-angle formula, Chapter 3.)
3. If the Ring Nebula is about a light-year in diameter and expanding at a velocity of 15 km/s, typical of planetary nebulae, how old is it? (*Hint*: $1 \text{ ly} = 9.46 \times 10^{12} \text{ km}$, and $1 \text{ year} = 3.16 \times 10^7 \text{ s}$.)
4. Suppose that a planetary nebula is 1.0 pc in diameter and the Doppler shifts in its spectrum show that it is expanding at 30 km/s. How old is it? (*Hint*: See Problem 3.)
5. A planetary nebula photographed 20 years ago and then photographed again today has increased its radius by 0.6 arc seconds. If Doppler shifts in its spectrum show that it is expanding at a velocity of 20 km/s, how far away is it? (*Hints*: First figure out how many parsecs it has increased in radius in 20 years. Then use the small-angle formula, Chapter 3.)
6. The Crab Nebula is now 1.35 pc in radius and is expanding at 1400 km/s. About when did the supernova occur?
7. The Cygnus Loop is now 2.6° in diameter and lies about 500 pc distant. If it is 10,000 years old, what was its average velocity of expansion? (*Hint*: Find its radius in parsecs first, using the small-angle formula, Chapter 3.)
8. The supernova remnant Cassiopeia A (Cas A) is expanding in radius at a rate of about 0.5 arc seconds per year. Doppler shifts show that the velocity of expansion is about 5700 km/s. How far away is the nebula?
9. Cassiopeia A has a radius of about 2.5 arc minutes. If it is expanding at 0.5 arc seconds per year, when did the supernova explosion occur? (Note that there is no record of a supernova being seen at that time.)

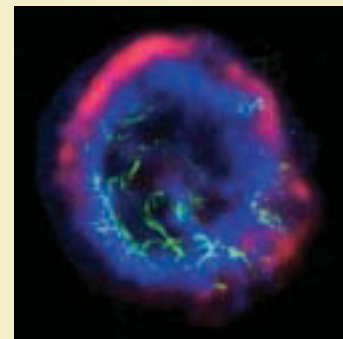
Learning to Look

1. What processes caused a medium-mass star to produce the nebula shown here? The nebula is now about 0.1 ly in diameter and still expanding. What will happen to it?



NASA/Hubble Heritage Team/STScI/AURA

2. The image here combines X-ray (blue), visible (green), and radio (red) images. Observations show the sphere is expanding at a high speed and is filled with very hot gas. What kind of object produced this nebula? Roughly how old do you think it must be?



NASA/CAC/SAO/CSIRO/ATNF/ATCA

14

Neutron Stars and Black Holes



Artist impression

Guidepost

In the last two chapters you have traced the story of stars from birth to death. By now you are asking a simple question, “What’s left?” The answer depends on the mass of the star. You already know that stars like the sun produce white dwarf corpses, but more massive stars leave behind the strangest beasts in the cosmic zoo.

Now you are ready to meet neutron stars and black holes, and your exploration will answer four essential questions:

— **How does theory predict the existence of neutron stars?**

— **How do astronomers know neutron stars really exist?**

— **How does theory predict the existence of black holes?**

— **How can astronomers be sure that black holes really exist?**

This chapter will show you more striking examples of how astronomers combine observations and theory to understand nature.

This chapter ends the story of individual stars, but it does not end the story of stars. In the next chapter, you will begin exploring the giant communities in which stars live—the galaxies.

A neutron star containing roughly the mass of the sun and only about 10 km in radius draws matter inward through a whirling disk of gas hot enough to emit X-rays. (NASA/Dana Berry)

*Almost anything is easier
to get into than out of.*

— AGNES ALLEN

GRAVITY ALWAYS WINS. No matter how long a star struggles to withstand its own gravity, it must eventually exhaust its fuels and die by collapsing. Those stars that do not destroy themselves in the process become one of three types of compact objects—white dwarfs, neutron stars, or black holes. Almost all of the energy available has been squeezed out of compact objects, and you find them in their final, high-density states.

You studied white dwarfs in the previous chapter. Here you will study the most extreme of the compact objects, and you need to compare evidence and theory with great care. Theory predicts the existence of these objects; but, by their nature, they are difficult to detect. To confirm the theories, astronomers have searched for real objects that can be identified as having the properties predicted by theory. That is, they have searched out real neutron stars and real black holes. No hero ever set off on a more difficult quest.

14-1 Neutron Stars

A **NEUTRON STAR** CONTAINING A LITTLE OVER 1 SOLAR MASS compressed to a radius of about 10 km can be left behind by a type II supernova. For comparison, a white dwarf has about the same mass but is about the size of Earth. A neutron star's density is so high that physicists calculate that the matter is stable only as a fluid of neutrons. Theory predicts that such an object would spin a number of times a second, be nearly as hot at its surface as the inside of the sun, and have a magnetic field a trillion times stronger than Earth's. Two questions should occur to you immediately. First, how could any theory predict such a wondrously unbelievable object? And second, do neutron stars really exist?

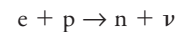
Theoretical Prediction of Neutron Stars

The neutron was discovered in the laboratory in February 1932. Only two years later, in January 1934, Caltech astronomers Walter Baade and Fritz Zwicky published a seminal paper. They showed that some novae in historical records were much more luminous than most and suggested that these were caused by the explosive collapse of a massive star in an explosion they named a supernova. The core of the star, they proposed, would form a small and tremendously dense sphere of neutrons, and Zwicky coined the term *neutron star*.

Over the following years, scientists applied the principles of quantum mechanics to see if such an object was indeed possible. Neutrons spin in much the way that electrons do, which means that neutrons must obey the Pauli exclusion principle. In other words, if neutrons are packed together tightly enough, they can

become degenerate just as electrons do. White dwarfs are supported by degenerate electrons, and quantum mechanics predicts that an even denser mass of neutrons could support itself by the pressure of degenerate neutrons.

How does the core of a collapsing star become a mass of neutrons? Nuclear physics provides an explanation. As the supernova begins, the core collapses inward. If the collapsing core is more massive than the Chandrasekhar limit of 1.4 solar masses, then it cannot reach stability as a white dwarf because the weight is too great to be supported by degenerate electrons. The collapse of the core continues, and the atomic nuclei are broken apart by gamma rays. Almost instantly, the increasing density forces the freed protons to combine with electrons and become neutrons by this reaction:



A side result is the production of a neutrino. Remember from the previous chapter that the burst of neutrinos (ν) during a supernova explosion helps blast the envelope of the star away, and the core is left behind as a neutron star.

Which stars produce neutron stars as remnants? As you saw in the previous chapter, a star of 8 solar masses or less can lose enough mass to die by forming a planetary nebula and then leaving behind a white dwarf. More massive stars also lose mass rapidly, but model calculations indicate they cannot shed mass fast enough to reduce their mass below the Chandrasekhar limit, so it seems likely that they must die in supernova explosions. Theoretical calculations suggest that stars that begin life on the main sequence with roughly 8 to 20 solar masses will leave behind neutron stars. Stars even more massive than that are thought to form black holes.

How massive can a neutron star be? That is a critical question and a difficult one to answer because scientists don't know the strength of pure neutron material. They can't make such matter in the laboratory, so its properties must be predicted theoretically. The most widely accepted calculations suggest that a neutron star cannot be more massive than about 3 solar masses. If a neutron star were more massive than that, the degenerate neutrons would not be able to support the weight, and the object would collapse (presumably into a black hole). Two of the most massive neutron stars observed have masses of 1.94 and 2.74 solar masses, which confirms the theory.

How big are neutron stars? Mathematical models predict that a neutron star should be only 10 or so kilometers in radius (■ Figure 14-1), which, combined with a typical mass, means it must have a density of almost 10^{15} g/cm³. On Earth, a sugar-cube-sized lump of this material would weigh 100 million tons. This is roughly the density of an atomic nucleus, so you can think of a neutron star as matter with absolutely all of the empty space squeezed out of it.

Simple physics, the same physics you have used in previous chapters to understand normal stars, predicts that neutron stars



■ **Figure 14-1**

A tennis ball and a road map illustrate the relative size of a neutron star. Such an object, containing slightly more than the mass of the sun, would fit with room to spare inside the beltway around Washington, D.C. (Photo by M. Seeds)

should be hot, spin rapidly, and have strong magnetic fields. You have seen that contraction heats the gas in a star. As gas particles fall inward, they pick up speed; and, when they collide, their high speeds become thermal energy. The sudden collapse of the core of a massive star to a radius of 10 km should heat it to a trillion degrees. Astronomers calculate that neutron stars should initially cool rapidly from that astonishingly high temperature because neutrinos can escape from their entire volume and carry energy away. After a few years neutron stars will cool down to a mere million degrees or so, and neutrinos won't be produced in bulk. From that point on, neutron stars should cool slowly because the heat can escape only from the surface, and neutron stars are so small they have little surface from which to radiate.

The principle of conservation of angular momentum predicts that neutron stars should spin rapidly. All stars rotate because they form from swirling clouds of interstellar matter. As a star collapses, it must rotate faster because it conserves angular momentum. Recall the example of an ice skater spinning slowly with her arms extended and then speeding up as she pulls her arms closer to her body (see Figure 5-7). In the same way, a collapsing star must spin faster as it pulls its matter closer to its axis of rotation. If the sun collapsed to a radius of 10 km, its period of rotation would increase from once every 25 days to over 20 times a second. You might expect the collapsed core of a massive star to rotate in the range of 10 to 100 times a second.

It isn't hard to understand why a neutron star should have a powerful magnetic field. The gas of a star is ionized, and that means the magnetic field cannot move easily through the gas.

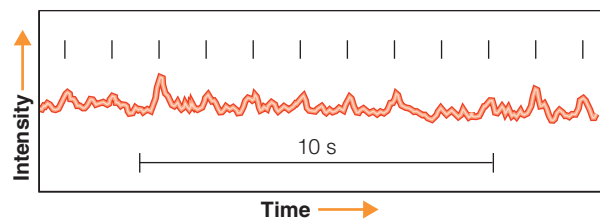
When the star collapses, the magnetic field is squeezed into a smaller volume, which can make the field as much as a billion times stronger. Because some stars start with magnetic fields over 1000 times stronger than the sun's, a neutron star could have a magnetic field as much as a trillion times stronger than the sun's. For comparison, that is about 10 million times stronger than any magnetic field ever produced in the laboratory.

Theory predicts the properties of neutron stars, but it also predicts that they should be difficult to observe. Neutron stars are very hot, so from your understanding of blackbody radiation you can predict they will radiate most of their energy in the gamma-ray and X-ray part of the spectrum, radiation that could not be observed in the 1940s and 1950s because astronomers could not put their telescopes above Earth's atmosphere. Also, the small surface areas of neutron stars mean that they will be faint objects. Consequently, astronomers of the mid-20th century were not surprised that none of the newly predicted neutron stars had been found. Neutron stars were, at that point, entirely theoretical objects.

The Discovery of Pulsars

In November 1967, Jocelyn Bell, a graduate student at Cambridge University in England, found a peculiar pattern in the data from a radio telescope. Unlike other radio signals from celestial bodies, this was a series of regular pulses (■ Figure 14-2). At first she and the leader of the project, Anthony Hewish, thought the signal was interference from Earthly sources, but they found it day after day in the same place in the sky. Clearly, it was celestial in origin.

Another possibility, that it came from a distant civilization, led them to consider naming it LGM, for Little Green Men. But within a few weeks, the team found three more objects in other parts of the sky pulsing with different periods. The objects were clearly natural, and the team dropped the name LGM in favor of



■ **Figure 14-2**

The 1967 detection of regularly spaced pulses in the output of a radio telescope led to the discovery of pulsars. This record of the radio signal from the first pulsar, CP 1919, contains regularly spaced pulses (marked by ticks). The period is 1.33730119 seconds.

pulsar—a contraction of *pulsing star*. The pulsing radio source Bell had observed with her radio telescope was the first known pulsar.

As more pulsars were found, astronomers argued over their nature. The periods ranged from 0.033 to 3.75 seconds and each one was nearly as exact as an atomic clock. However, months of observation showed that many of the periods were slowly growing longer by a few billionths of a second per day. Whatever produced the regular pulses had to be highly precise, nearly as exact as an atomic clock, but also gradually slowing down.

It was easy to eliminate possibilities. Pulsars could not be ordinary stars. A normal star, even a small white dwarf, is much too big to pulse that fast. Nor could a star with a hot spot on its surface spin fast enough to produce the pulses. Even a small white dwarf would fly apart if it spun 30 times a second.

The pulses themselves gave the astronomers a clue. The pulses lasted only about 0.001 second, placing an upper limit on the size of the object producing the pulse. If a white dwarf blinked on and then off in that interval, you would not see a 0.001-second pulse. That's because the point on the white dwarf closest to Earth would be about 6000 km closer to you, and light from that spot would arrive 0.022 second before the light from the bulk of the white dwarf. So its short blink would be smeared out into a longer pulse. This is an important principle in astronomy—an object cannot change its brightness appreciably in an interval shorter than the time light takes to cross its diameter. If pulses from pulsars are no longer than 0.001 second, then the objects cannot be larger than 300 km (190 miles) in diameter, and could be much smaller.

Only a neutron star is small enough to be a pulsar. In fact, a neutron star is so small that it couldn't pulsate slowly enough, but it can spin as fast as 1000 times a second without flying apart. The missing link between pulsars and neutron stars was found in 1968, when astronomers discovered a pulsar at the heart of the Crab Nebula (Figure 13-16). The Crab Nebula is a supernova remnant, and theory predicts that some supernovae leave behind neutron stars. The short pulses and the discovery of the pulsar in the Crab Nebula were strong evidence that pulsars are neutron stars.

A Model Pulsar

As you have noticed before, scientists often work by building a model of a natural phenomenon—not a physical model made of plastic and glue, but an intellectual conception of how nature works in a specific instance. The scientists' model may be limited and incomplete, but it helps them organize their understudying.

The modern model of a pulsar has been called the **lighthouse model** and is shown in **The Lighthouse Model of a Pulsar** on pages 284–285. Notice three important points:

1 A pulsar does not pulse but rather emits beams of radiation that sweep around the sky as the neutron star rotates. If the beams do not sweep over Earth, the pulses will not be detectable by Earth's radio telescopes.

2 The mechanism that produces the beams involves extremely high energies and is not fully understood.

3 Modern space telescopes observing from above Earth's atmosphere can image details around young neutron stars and even locate isolated neutron stars whose beams of electromagnetic radiation do not sweep over Earth.

Neutron stars are not simple objects, and modern astronomers need to use both general relativity and quantum mechanics to try to understand them. Nevertheless, astronomers know enough to tell the life story of pulsars.

The Evolution of Pulsars

When a pulsar first forms, it is spinning fast, perhaps a hundred times a second. The energy it radiates into space comes from its energy of rotation, so as it blasts beams of radiation outward, its rotation slows. The average pulsar is apparently only a few million years old, and the oldest are about 10 million years old. Presumably, older neutron stars rotate too slowly to generate detectable radio beams.

You can expect that a young neutron star should emit powerful beams of radiation. The Crab Nebula is an example. Only about 950 years old, the Crab pulsar is so powerful it emits photons all across the electromagnetic spectrum, at radio, infrared, visible, X-ray, and gamma-ray wavelengths (■ Figure 14-3). Careful measurements of its brightness with high-speed instruments show that it blinks twice for every rotation. When one beam sweeps almost directly over Earth, astronomers detect a strong pulse. Half a rotation later, the edge of the other beam brushes over Earth, and astronomers detect a weaker pulse.

Only the most energetic pulsars produce short-wavelength photons and thus pulse at visible wavelengths. The Crab Nebula pulsar is young and powerful, and it produces visible pulses. So does another young pulsar called the Vela pulsar (located in the Southern Hemisphere constellation Vela). Compared with most pulsars, the Vela pulsar is fast, pulsing about 11 times a second and, like the Crab Nebula pulsar, is located inside a supernova remnant. Its age is estimated at a relatively young 20,000 to 30,000 years.

The Fermi Gamma-Ray Space Telescope has detected a new kind of pulsar that pulses in pure gamma rays. It is not clear how these pulses are produced, but because gamma rays are extremely short-wavelength, high-energy photons, the process must involve very high energies. At least one of those gamma-ray pulsars is located inside a supernova remnant that is only about 10,000 years old.

The electromagnetic energy in the beams is only a small part of the energy emitted by a pulsar. Roughly 99.9 percent of the energy flowing away from a pulsar is carried as a **pulsar wind** of high-speed atomic particles. This can produce small, high-energy nebulae near a young pulsar (■ Figure 14-4).

Figure 14-3

High-speed images of the Crab Nebula pulsar show it pulsing at visual wavelengths and at X-ray wavelengths. (© AURA, Inc., NOAO, KPNO) The period of pulsation is 33 milliseconds, and each cycle includes two pulses as its two beams of unequal intensity sweep over Earth. (Courtesy F. R. Harnden Jr., from *The Astrophysical Journal*, published by the University of Chicago Press; © 1984 The American Astronomical Society)

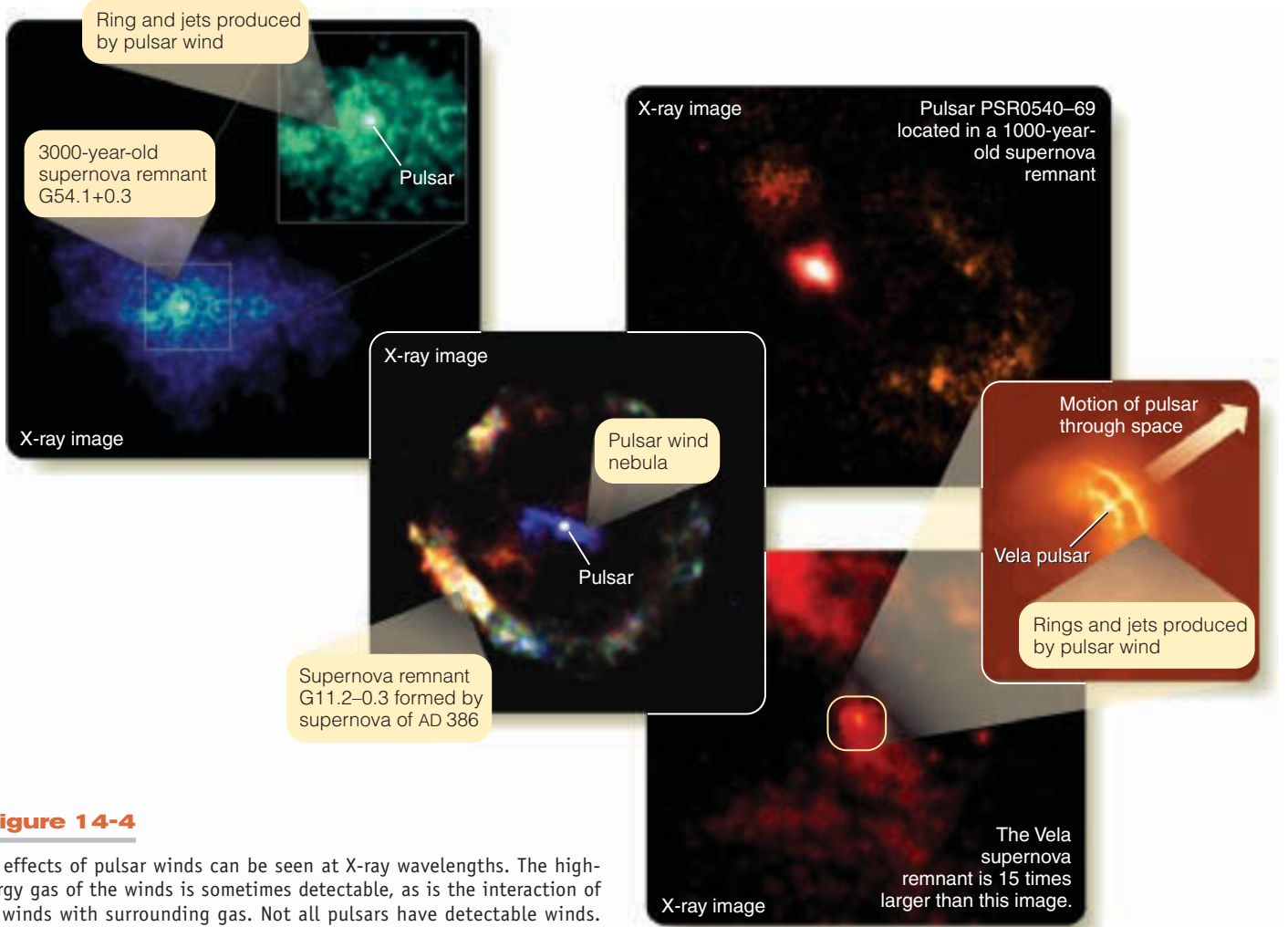
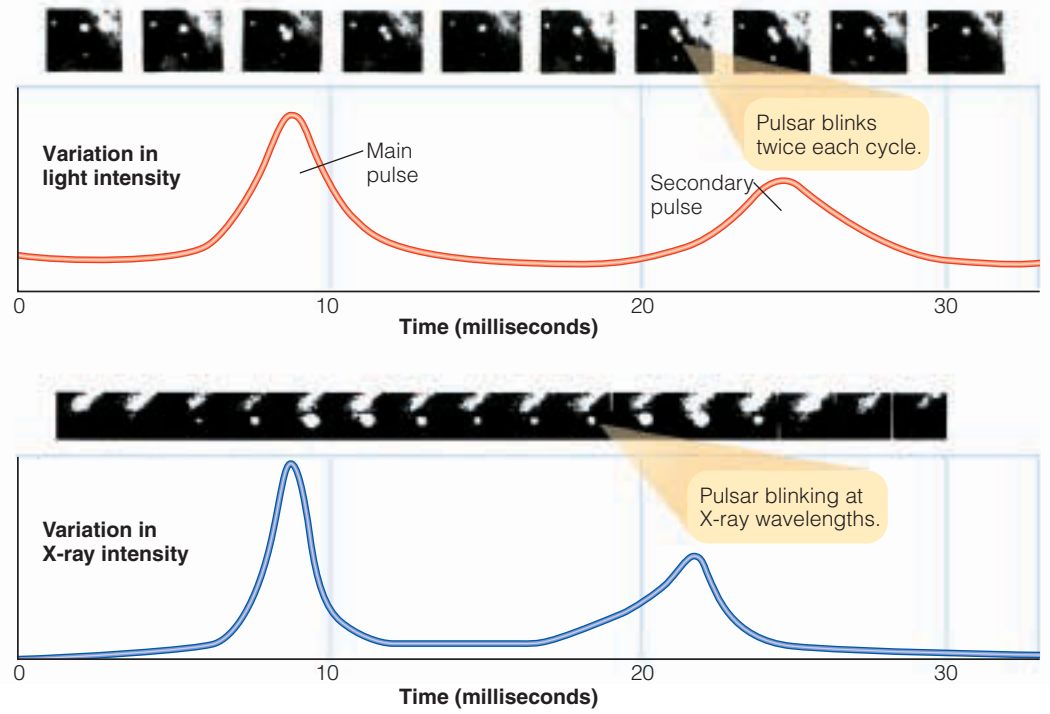


Figure 14-4

The effects of pulsar winds can be seen at X-ray wavelengths. The high-energy gas of the winds is sometimes detectable, as is the interaction of the winds with surrounding gas. Not all pulsars have detectable winds. (NASA/CXC/SAO/U. Mass; F. Lu/McGill; V. Kaspi)

The Lighthouse Model of a Pulsar



1 Astronomers think of pulsars not as pulsing objects but rather as objects emitting beams. As they spin, the beams sweep around the sky; when a beam sweeps over Earth, observers detect a pulse of radiation. Understanding the details of this lighthouse model is a challenge, but the implications are clear. Although a neutron star is only a few kilometers in radius, it can produce powerful beams. Also, observers tend to notice only those pulsars whose beams happen to sweep over Earth.

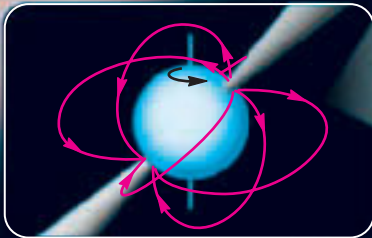
In this artist's conception, gas trapped in the neutron star's magnetic field is excited to emit light and outline the otherwise invisible magnetic field.

Beams of electromagnetic radiation would probably be invisible unless they excited local gas to glow.

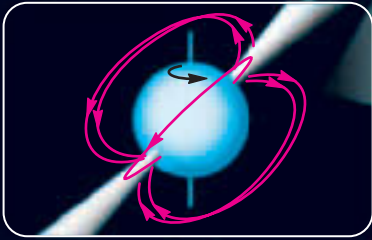
What color should an artist use to paint a neutron star?
With a temperature of a million degrees, the surface emits most of its electromagnetic radiation at X-ray wavelengths. Nevertheless, it would probably look blue-white to your eyes.

2 How a neutron star can emit beams is one of the challenging problems of modern astronomy, but astronomers have a general idea. A neutron star contains a powerful magnetic field and spins very rapidly. The spinning magnetic field generates a tremendously powerful electric field, and the field causes the production of electron-positron pairs. As these charged particles are accelerated through the magnetic field, they emit photons in the direction of their motion, which produce powerful beams of electromagnetic radiation emerging from the magnetic poles.

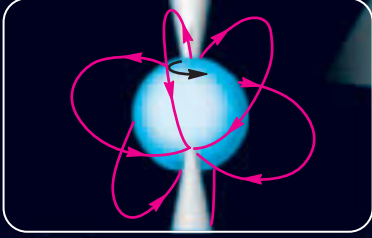
Neutron Star Rotation with Beams



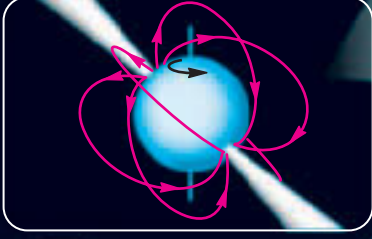
As in the case of Earth, the magnetic axis of a neutron star could be inclined to its rotational axis.



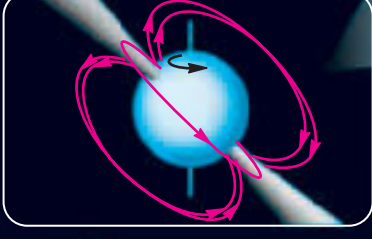
The rotation of the neutron star will sweep its beams around like beams from a lighthouse.



While a beam points roughly toward Earth, observers detect a pulse.

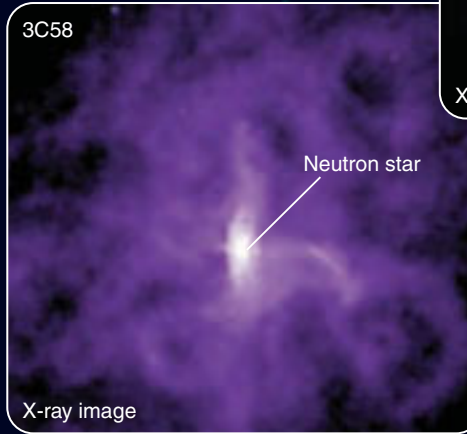


While neither beam is pointed toward Earth, observers detect no energy.



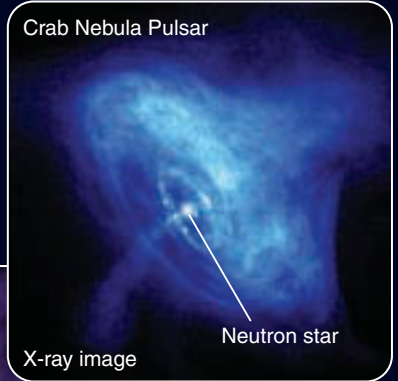
Beams may not be as exactly symmetric as in this model.

3 X-ray observations of young pulsars show that they are surrounded by disks of excited matter and emit powerful jets of excited gas. The disks and jets are shaped by electromagnetic fields, and the jets may curve if they encounter magnetic fields.

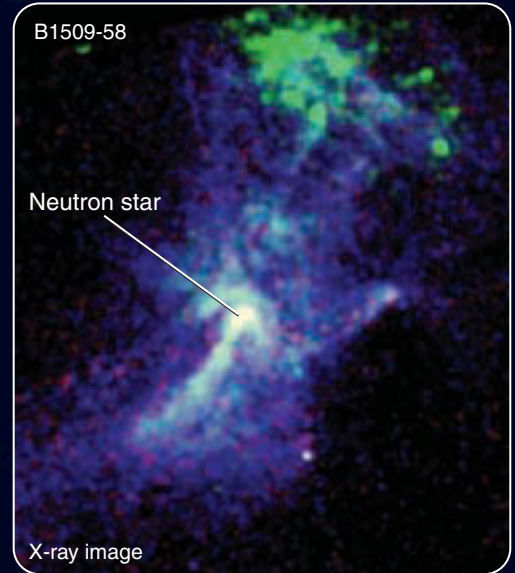


The pulsar 3C58 above was produced by the supernova seen in AD 1181. It pulses 15 times per second and is ejecting jets in both directions.

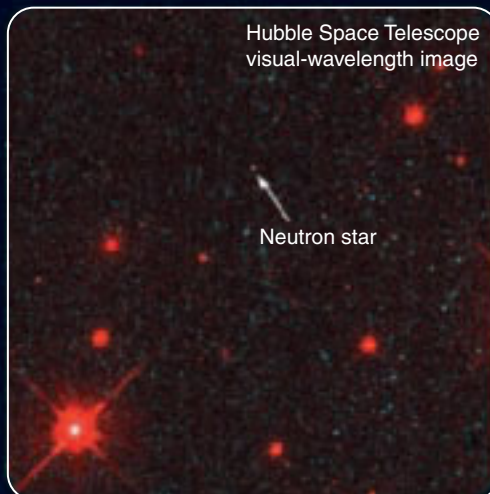
The pulsar B1509-58 at right is only 1700 years old, young for a pulsar. It is ejecting a thin jet almost 20 ly long. The nebulosity at the top of the image is part of the enclosing supernova remnant excited by energy from the pulsar.



The Crab Nebula Pulsar above was produced by the supernova of AD 1054. It pulses 30 times a second, and X-ray images can detect rapid flickering changes in the disk.



NASA



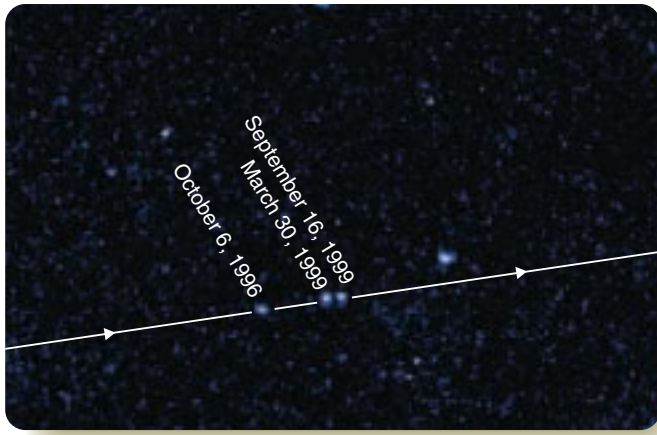
NASA

3a If a pulsar's beams do not sweep over Earth, observers detect no pulses, and the neutron star is difficult to find. A few such objects are known, however. The Puppis A supernova remnant is about 4000 years old and contains a point source of X-rays believed to be a neutron star. The isolated neutron star in the right-hand image has a temperature of 700,000 K.

NASA/CXC/ASU/J. Hester et al.

NASA/CXC/SAO/P. Slane et al.

NASA/CXC/SAO/B. Gaensler et al.



■ **Figure 14-5**

Many neutron stars have high velocities through space. Here the neutron star known as RXJ 185635-3754 was photographed on three different dates as it rushed past background stars. (V. Kaspi/NASA)

You might expect to find all pulsars inside supernova remnants, but the statistics must be examined with care. Many supernova remnants probably do contain pulsars, but their beams never sweep over Earth. Also, some pulsars move through space at high velocity (■ Figure 14-5), quickly leaving their supernova remnants behind. Evidently supernova explosions can occur asymmetrically, perhaps because of the violent turbulence in the exploding core, and that can kick a neutron star away with a high velocity through space. Some supernovae probably occur in binary systems and fling the two stars apart at high velocity. In any case, pulsars are known to have such high velocities that many probably escape the disk of our galaxy. Finally, you must remember that a pulsar can remain detectable for 10 million years or so, but a supernova remnant cannot survive more than about 50,000 years before it is mixed into the interstellar medium. For all these reasons, you should not be surprised that most pulsars are not in supernova remnants and that most supernova remnants do not contain pulsars.

Astronomers conclude that the 1987 explosion of Supernova 1987A formed a neutron star. As you read in the previous chapter, a burst of neutrinos was detected passing through Earth; theory predicts that the collapse of a massive star's core into a neutron star produces such a burst of neutrinos, so the detection of the neutrinos is evidence that the supernova produced a neutron star. At first the neutron star will be hidden at the center of the expanding shells of gas ejected into space; but, as the gas expands and thins, astronomers expect someday to be able to detect the neutron star. Even if its beams don't sweep over Earth, astronomers should eventually be able to detect its X-ray and gamma-ray emission. Although no neutron star has yet been detected, astronomers continue to watch the site, hoping to see a newborn pulsar.

One reason pulsars are so fascinating is the extreme conditions found in spinning neutron stars. To see natural processes

of even greater violence, you have only to look at pulsars in binary systems.

Binary Pulsars

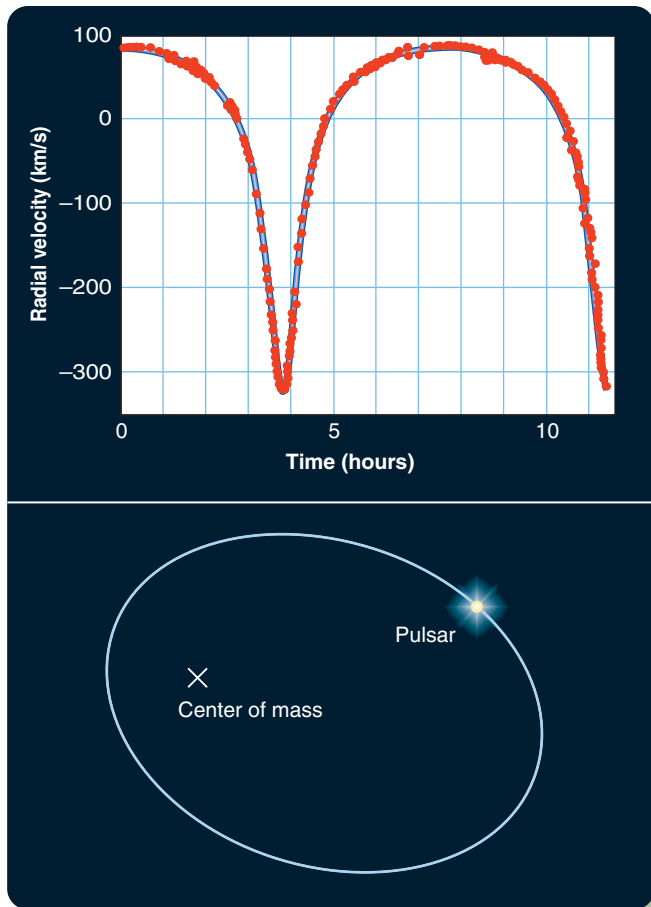
Nearly 2000 pulsars are now known, and some are located in binary systems. These pulsars are of special interest because astronomers can learn more about the neutron star by studying the orbital motions of the binary. Also, in some cases, mass can flow from the companion star onto the neutron star, and that produces high-energy violence.

The first binary pulsar was discovered in 1974 when astronomers Joseph Taylor and Russell Hulse noticed that the pulse period of the pulsar PSR 1913+16 was changing. The period first grew longer and then grew shorter in a cycle that took 7.75 hours. Thinking of the Doppler shifts seen in spectroscopic binaries, the radio astronomers realized that the pulsar had to be in a binary system with an orbital period of 7.75 hours. When the orbital motion of the pulsar carries it away from Earth, astronomers see the pulse period lengthen slightly—a redshift. Then, when the pulsar rounds its orbit and approaches Earth, they see the pulse period shorten slightly—a blueshift. From these changing Doppler shifts, Taylor and Hulse calculated the radial velocity of the pulsar around its orbit just as if it were a spectroscopic binary star. The resulting graph of radial velocity versus time was then analyzed to find the shape of the pulsar's orbit (■ Figure 14-6). The analysis of PSR 1913+16 showed that the binary system consists of two neutron stars, one of which is “silent,” separated by a distance roughly equal to the radius of our sun.

Yet another surprise was hidden in the motion of PSR 1913+16. In 1916, Einstein's general theory of relativity described gravity as a curvature of space-time. Einstein realized that any rapid change in a gravitational field should spread outward at the speed of light as **gravitational radiation**. Gravity waves have not been detected yet, but Taylor and Hulse were able to show that the orbital period of the binary pulsar is slowly growing shorter because the stars are radiating orbital energy away as gravitational radiation and gradually spiraling toward each other. (Normal binary stars are too far apart and orbit too slowly to emit significant gravitational radiation.) Taylor and Hulse won the Nobel Prize in 1993 for their work with binary pulsars.

Dozens of pulsars have been found orbiting stars of various kinds; by analyzing the Doppler shifts in their pulse periods, astronomers can estimate the masses of the neutron stars. Typical masses are about 1.4 solar masses, in good agreement with models of neutron stars.

In 2004, radio astronomers announced the discovery of a double pulsar: two pulsars that orbit each other in only 2.4 hours. The spinning beams from both pulsars sweep over Earth (■ Figure 14-7). One spins 44 times a second, and the other spins



■ **Figure 14-6**

The radial velocity of pulsar PSR 1913+16 can be found from the Doppler shifts in its pulsation. Analysis of the radial velocity curve allows astronomers to determine the pulsar's orbit. Here the center of mass does not appear to be at a focus of the elliptical orbit because the orbit is inclined to the line of sight from Earth. (Adapted from data by Joseph Taylor and Russell Hulse)

once every 2.8 seconds. This system is a pulsar jackpot because the orbits are nearly edge-on to Earth and the powerful magnetic fields and the gas trapped in the fields eclipse each other, giving astronomers the chance to study their size and structure. Furthermore, the theory of general relativity predicts that these pulsars are emitting gravitational radiation and that their separation is decreasing by 7 mm per year. The two neutron stars will merge in 85 million years, presumably to trigger a violent explosion. In the meantime, the steady decrease in orbital period can be measured, giving astronomers a further test of general relativity and gravitational radiation.

In addition to producing gravitational radiation, a neutron star's intense gravitational field means that binary pulsars can be sites of tremendous violence if matter is transferred from a star to a neutron star. The gravitational field is so strong that an astronaut stepping onto the surface of a neutron star would be instantly smushed into a layer of matter only 1 atom thick.



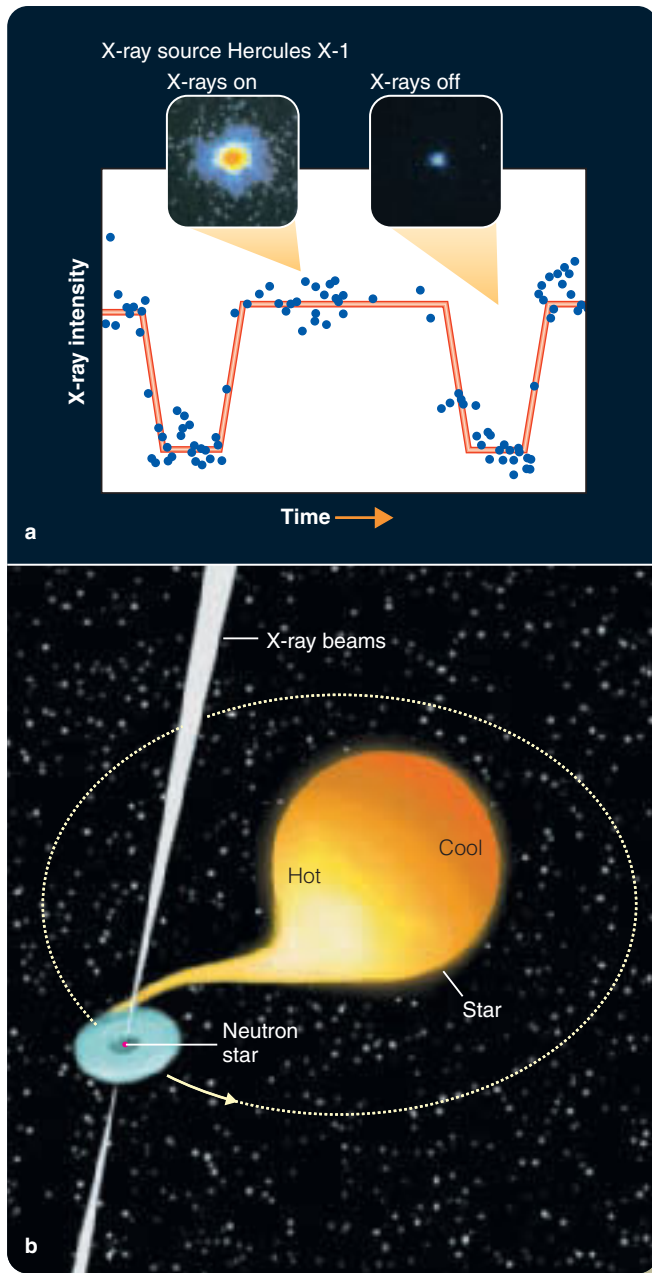
■ **Figure 14-7**

Artist's impression of the double pulsar. One star must have exploded to form a pulsar, and later the other star did the same. Gravitational radiation causes the neutron stars to spiral toward each other, and they will merge in 85 million years, presumably then triggering a violent explosion. (John Rowe Animations)

Matter falling into this gravitational field releases titanic amounts of energy. If you dropped a single marshmallow onto the surface of a neutron star from a distance of 1 AU, it would hit with an impact equivalent to a 3-megaton nuclear warhead. In general, a particle falling from a large distance to the surface of a neutron star will release energy equivalent to $0.2 mc^2$, where m is the particle's mass at rest and c is the speed of light. Even a small amount of matter flowing from a companion star to a neutron star can generate high temperatures and release X-rays and gamma rays.

Hercules X-1 is an example of such an active system; it contains a 2-solar-mass star and a neutron star that orbit each other with a period of 1.7 days (■ Figure 14-8). Matter flowing from the normal star into an accretion disk around the neutron star reaches temperatures of millions of degrees and emits a powerful X-ray glow. Interactions of the gas with the neutron star's magnetic field produce beams of X-rays that sweep around with the rotating neutron star (Figure 14-8b). Earth receives a pulse of X-rays every time a beam points this way. The X-rays shut off completely every 1.7 days when the neutron star is eclipsed behind the normal star. Hercules X-1 is a complex system with many different high-energy processes going on simultaneously, but this quick sketch serves to illustrate how complex and powerful such binary systems are during mass transfer.

The X-ray source 4U 1820-30 illustrates another way neutron stars can interact with normal stars. In this system, a neutron star and a white dwarf orbit their center of mass with a



■ **Figure 14-8**

Sometimes the X-ray pulses from Hercules X-1 are on, and sometimes they are off. A graph of X-ray intensity versus time looks like the light curve of an eclipsing binary. (Insets: J. Trümper, Max-Planck Institute) (b) In Hercules X-1, matter flows from a star into an accretion disk around a neutron star producing X-rays, which heat the near side of the star to 20,000 K compared with only 7000 K on the far side. X-rays turn off when the neutron star is eclipsed behind the star.

period of only 11 minutes (■ Figure 14-9a and b). The separation between the two objects is only about one-third the distance between Earth and the moon. To explain how such a very close pairing could originate, theorists suggest that a neutron star collided with a giant star and went into an orbit inside the star. (Recall the low density of the outer envelope of giant stars.) The

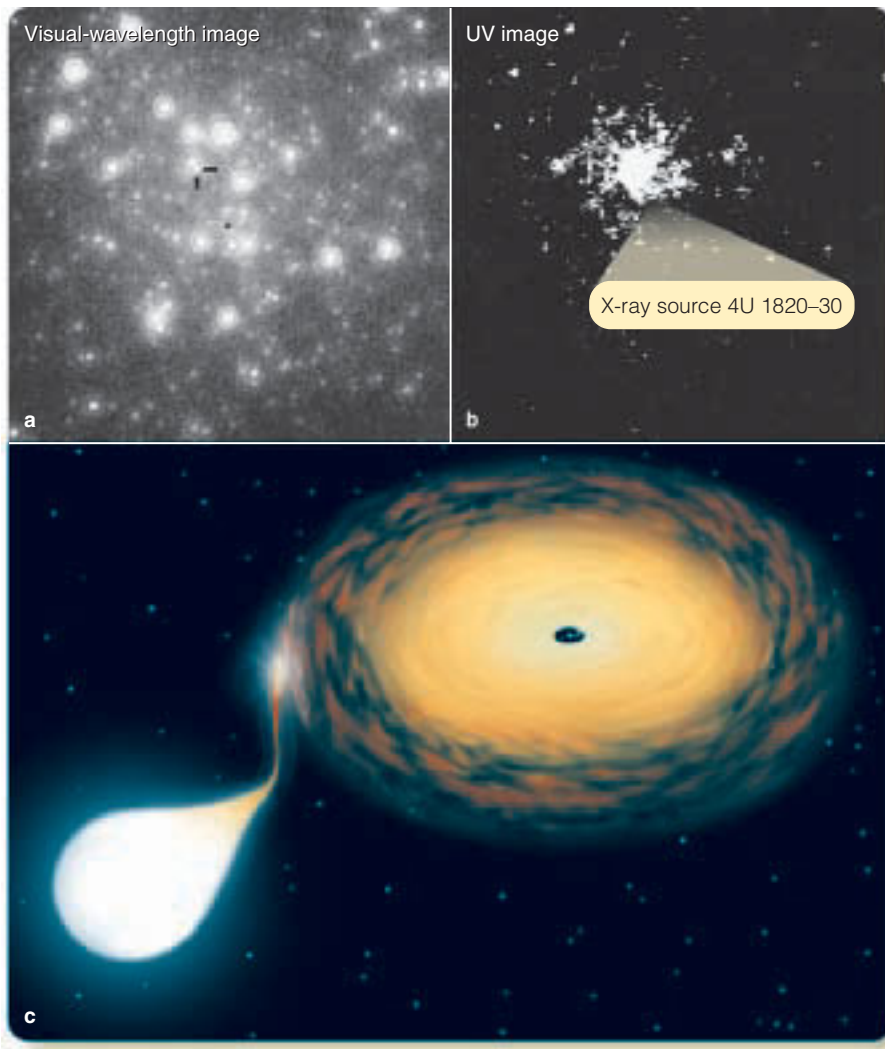
neutron star would gradually eat away the giant star's envelope from the inside, and the star would collapse into a white dwarf. Matter still flows from the white dwarf into an accretion disk and then down to the surface of the neutron star (Figure 14-9c), where it accumulates in a degenerate layer until it ignites helium fusion to produce a burst of X-rays. Objects called **X-ray bursters** are thought to be such binary systems involving mass transferred to a neutron star, and the bursts repeat each time a large enough layer of degenerate fuel accumulates. Notice the similarity between this mechanism and that responsible for novae (see Chapter 13).

The Fastest Pulsars

Your knowledge of pulsars suggests that newborn pulsars should blink rapidly, and old pulsars should blink slowly. In fact, the handful that blink the fastest may be quite old. One of the fastest known pulsars is cataloged as Terzan 5ad in the constellation Sagittarius. It pulses 716 times a second and is slowing down only slightly. The energy stored in the rotation of a neutron star at this rate is equal to the total energy of a supernova explosion, so it seemed difficult at first to explain this pulsar. It now appears that Terzan 5ad is an old neutron star that has gained mass and rotational energy from a companion in a binary system. Like water hitting a mill wheel, the matter falling on the neutron star has spun it up to 716 rotations per second. With its weak magnetic field, it slows down very gradually and will continue to spin rapidly for a very long time.

A number of other very fast pulsars have been found. They are generally known as **millisecond pulsars** because their pulse periods and therefore their periods of rotation are almost as short as a millisecond (0.001 s). This rapid rotation produces some fascinating physics. If a neutron star 10 km in radius spins 716 times a second, as does Terzan 5ad, then its equator must be traveling about 45,000 km/s. That is fast enough to flatten the neutron star into an ellipsoidal shape and is nearly fast enough to break it up. The fastest known pulsar, XTEJ1739-285, spins 1122 times a second. It appears to have been spun up by matter flowing from its companion star and is very near the breakup speed for an object composed of pure neutrons.

The hypothesis that the millisecond pulsars are spun up by mass transfer from a companion star is quite reasonable, but astronomers demand evidence, and evidence has been found. For example, the pulsar PSR J 1740-5340 has a period of 42 milliseconds and is orbiting a bloated red star from which it is gaining mass. This appears to be a pulsar caught in the act of being spun up to high speed. For another example, consider the X-ray source XTEJ1751-305, a pulsar with a period of only 2.3 milliseconds. X-ray observations show that it is gaining mass from a companion star. The orbital period is only 42 minutes, and the mass of the companion star is only 0.014 solar mass. The evidence suggests this neutron star has devoured all but the last morsel of its binary partner.



■ **Figure 14-9**

(a) At visible wavelengths, the center of star cluster NGC 6624 is crowded with stars. (b) In the ultraviolet, one object stands out, an X-ray source consisting of a neutron star orbiting a white dwarf. (c) An artist's conception shows matter flowing from the white dwarf into an accretion disk around the neutron star. (a and b, Ivan King and NASA/ESA)

“Show me,” say scientists; and, in the case of neutron stars, the evidence seems so strong that astronomers have great confidence that such objects really do exist. Other theories that describe their formation, their evolution, and how they emit beams of radiation are less certain, but continuing observations at many wavelengths are expanding astronomers’ understanding of these last embers of massive stars. In fact, precise observations have turned up some objects no one expected.

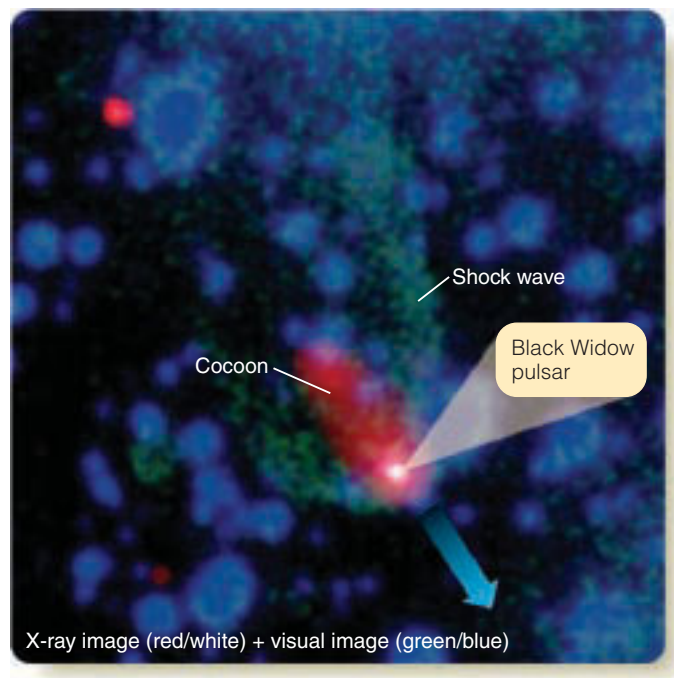
Pulsar Planets

Because a pulsar’s period is so precise, astronomers can detect tiny variations by comparing their observations with atomic clocks. When astronomers checked pulsar PSR B1257+12, they found variations in the period of pulsation much like those caused by the orbital motion of a binary pulsar (■ Figure 14-11a). However, in the case of PSR B1257+12, the

Although some millisecond pulsars have binary companions, some are solitary neutron stars. A pulsar known as the Black Widow may reveal how a fast pulsar can lack a companion. The Black Widow has a period of 1.6 milliseconds, meaning it is spinning 622 times per second, and it orbits with a low-mass companion. Presumably the neutron star was spun up by mass flowing from the companion, but spectra show that the blast of radiation and high-energy particles from the neutron star is now boiling away the surface of the companion. The Black Widow has eaten its fill and is now evaporating the remains of its companion. It will soon be a solitary millisecond pulsar (■ Figure 14-10).

■ **Figure 14-10**

The Black Widow pulsar and its companion star are moving rapidly through space, creating a shock wave like the bow wave of a speedboat. The shock wave confines high-energy particles shed by the pulsar into an elongated cocoon (red). (X-ray: NASA/CXC/ASTRON/B. Stappers et al.; Optical: AAO/J. Bland-Hawthorn & H. Jones)



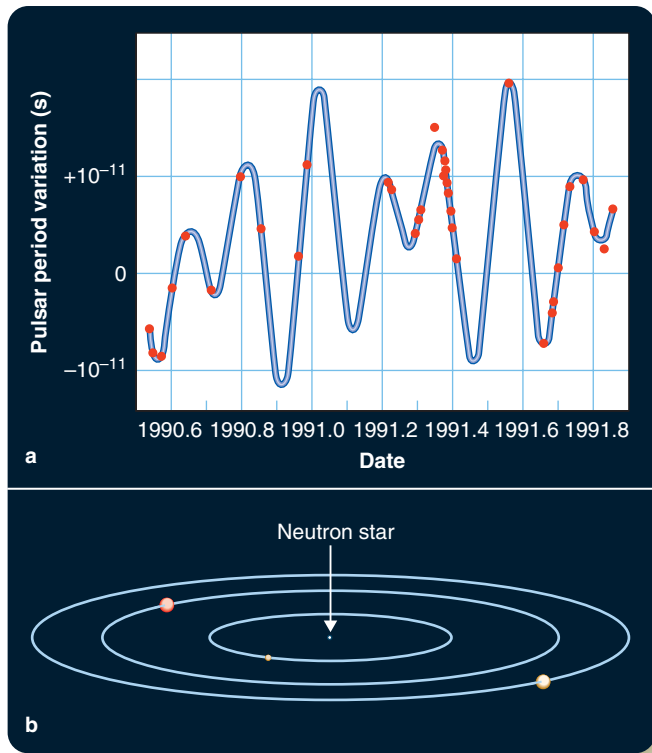


Figure 14-11

(a) The dots in this graph are observations showing that the period of pulsar PSR1257+12 varies from its average value by a fraction of a billionth of a second. The blue line shows the variation that would be produced by planets orbiting the pulsar. (b) As the planets orbit the pulsar, they cause it to wobble by less than 800 km, a distance that is invisibly small in this diagram. (Adapted from data by Alexander Wolszczan)

variations were much smaller; and, when they were interpreted as Doppler shifts, it became evident that the pulsar was being orbited by at least two objects with planet-like masses of 4.1 and 3.8 Earth masses. The gravitational tugs of these planets make the pulsar wobble about the center of mass of the system by no more than 800 km, producing the observed tiny changes in period (Figure 14-11b).

Astronomers greeted this discovery with both enthusiasm and skepticism. As usual, they looked for ways to test the hypothesis. Simple gravitational theory predicts that planets in the same system should interact and slightly modify each other's orbits. When the data were analyzed, that interaction was found, further confirming the existence of the planets. In fact, later data revealed the presence of a third planet with only 1/40 the mass of Earth, about twice the mass of Earth's moon. This illustrates the astonishing precision of studies based on pulsar timing.

Astronomers wonder how a neutron star can have planets. The three planets that orbit PSR B1257+12 are closer to the pulsar than Venus is to the sun. Any planets that orbited a star that closely would have been absorbed or vaporized when the star

expanded to become a supergiant. Furthermore, the supernova explosion would have suddenly reduced the mass of the star and allowed any orbiting planets to escape from their orbits. So how can planets exist there? One suggestion is that these planets are the remains of a stellar companion that was devoured by the neutron star. In fact, PSR B1257+12 spins very fast (161 pulses per second), suggesting that it was spun up in a binary system. However, the Spitzer Space Telescope observing in the infrared has detected a ring of gas and dust around a different rapidly spinning neutron star. If supernova explosions can leave such rings of material behind, then planets could form from the accumulation of matter in the rings.

PSR B1257+12 is not unique. Another planet has been found orbiting a neutron star that is part of a binary system with a white dwarf. Because this system is located in a very old star cluster and contains a white dwarf, astronomers suspect that the planet may be very old, dating back to the formation of that system rather than being debris from the supernova explosion that made the neutron star. Planets probably orbit other neutron stars, and small shifts in the timing of the pulses may eventually reveal their presence.

You can imagine what these worlds might be like. Formed from the remains of elderly stars, they might have chemical compositions richer in heavy elements than Earth. You can imagine visiting these worlds, landing on their surfaces, and hiking across their valleys and mountains. Above you, the neutron star would glitter in the sky, a tiny point of light.

SCIENTIFIC ARGUMENT

Why are neutron stars easier to detect at X-ray wavelengths?

This argument draws together a number of ideas you know from previous chapters. First, recall that a neutron star is very hot because of the heat released when it contracts to a radius of 10 km. It could easily have a surface temperature of 1,000,000 K, and Wien's law (see Chapter 7) tells you that such an object will radiate most intensely at a very short wavelength—X-rays. Normal stars are much cooler and emit only weak X-rays unless they have hot accretion disks. At visual wavelengths, stars are bright, and neutron stars are faint, but at X-ray wavelengths, the neutron stars stand out from the crowd.

Now build a new argument as if you were seeking funds for a research project. **What observations would you make to determine whether a newly discovered pulsar was young or old, single or a member of a binary system, alone or accompanied by planets?**

14-2 Black Holes

YOU HAVE NOW STUDIED white dwarfs and neutron stars, two of the three end states of dying stars. Now it's time to think about the third end state—black holes.

Although the physics of black holes is difficult to discuss without using sophisticated mathematics, simple logic is sufficient to predict that they should exist. The problem is to confirm that they are real. What objects observed in the heavens could be real black holes? More difficult than the search for neutron stars, the quest for black holes has nevertheless met with success.

You can begin by considering a simple question. How fast must an object travel to escape from the surface of a celestial body?

Escape Velocity

Suppose you threw a baseball straight up. How fast must you throw it if it is not to come down? Of course, gravity will always pull back on the ball, slowing it, but if the ball is traveling fast enough to start with, it will never come to a stop and fall back. Such a ball will escape from Earth.

In Chapter 5 you learned that the escape velocity is the initial velocity an object needs to escape from a celestial body (■ Figure 14-12). Whether you are discussing a baseball leaving Earth or a particle escaping a collapsing star, escape velocity depends on two things, the mass of the celestial body and the distance from the center of mass to the escaping object. If the celestial body has a large mass, its gravity is strong, and you need a high velocity to escape; but, if you begin your journey farther from the center of mass, the velocity needed is less. For example, to escape from Earth, a spaceship would have to leave Earth's surface at 11 km/s (25,000 mph), but if you could launch spaceships from the top of a tower 1000 miles high, the escape velocity would be only 10 km/s (22,000 mph).

If you could make an object massive enough or small enough, its escape velocity could be greater than the speed of light. Relativity says that nothing can travel faster than the speed of light, so even photons, which have no mass, would be unable to escape. Such a small, massive object could never be seen because light could not leave it.

Long before Einstein and relativity, the Reverend John Mitchell, a British gentleman astronomer, realized the peculiar consequences of Newton's laws of gravity and motion. In 1783, he pointed out that an object 500 times the radius of the sun but of the same density would have an escape velocity greater than the speed of light. Then, "all light emitted from such a body would be made to return towards it." Mitchell didn't know it, but he was talking about a black hole.

Schwarzschild Black Holes

If the core of a star contains more than 3 solar masses when it collapses, no force can stop it. It cannot stop collapsing when it reaches the density of a white dwarf because degenerate electrons cannot support that weight, and it cannot stop when it reaches the density of a neutron star because not even degenerate neutrons can support that weight. No force remains to stop the object from collapsing to zero radius.



■ **Figure 14-12**

Escape velocity, the velocity needed to escape from a celestial body, depends on mass. The escape velocity at the surface of a very small body would be so low you could jump into space. Earth's escape velocity is much larger, about 11 km/s (25,000 mph).

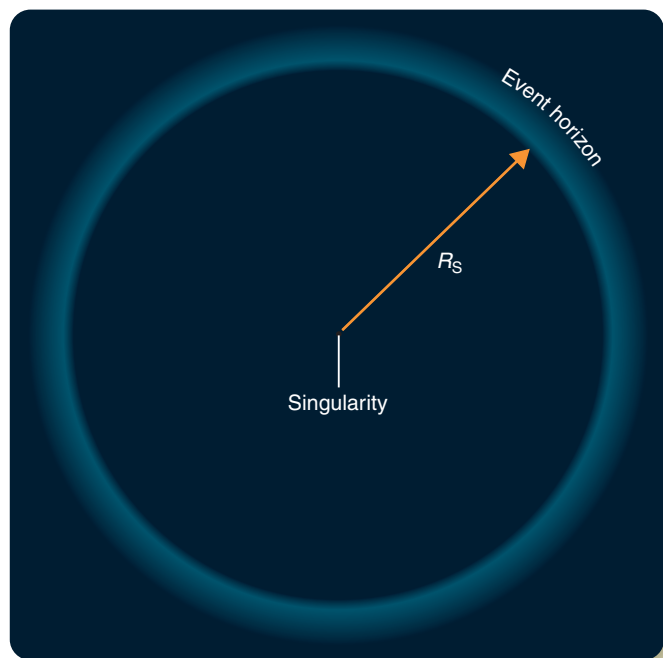
As an object collapses, its density and the strength of its surface gravity increase. If an object collapses to zero radius, its density and gravity become infinite. Mathematicians call such a point a **singularity**, but in physical terms it is difficult to imagine an object of zero radius. Some theorists believe that a singularity is impossible and that the laws of quantum physics must somehow halt the collapse at some subatomic radius roughly 10^{20} times smaller than a proton. Astronomically, it seems to make little difference.

If the contracting core of a star becomes small enough, the escape velocity in the region of space around it is so large that no light can escape. This means you can receive no information about the object or about the region of space near it. Because it emits no light, such a region is called a **black hole**. If the core of an exploding star collapsed into a black hole, the expanding outer layers of the star could produce a supernova remnant, but the core would vanish without a trace.

To understand black holes, you should consider relativity. In 1916, Albert Einstein published a mathematical theory of space

and time that became known as the general theory of relativity. Einstein treated space and time as a single entity called space-time. His equations showed that gravity could be described as a curvature of space-time, and almost immediately the astronomer Karl Schwarzschild found a way to solve Einstein's equations to describe the gravitational field around a single, non-rotating, electrically neutral lump of matter. That solution contained the first general relativistic description of a black hole, and non-rotating, electrically neutral black holes are now known as Schwarzschild black holes. In recent decades, theorists such as Roy Kerr and Stephen Hawking have found ways to apply the sophisticated mathematical equations of the general theory of relativity and quantum mechanics to describe charged, rotating black holes. For this discussion, the differences are minor, and you may proceed as if all black holes were Schwarzschild black holes.

Schwarzschild's solution shows that if matter is packed into a small enough volume, then space-time curves back on itself. Objects can follow paths that lead into the black hole, but no path leads out, so nothing can escape. Because not even light can escape, the inside of the black hole is totally beyond the view of an outside observer. The **event horizon** is the boundary between the isolated volume of space-time and the rest of the universe, and the radius of the event horizon is called the **Schwarzschild radius**, R_s . A collapsing stellar core must shrink inside its Schwarzschild radius to become a black hole (■ Figure 14-13).



■ **Figure 14-13**

A black hole forms when an object collapses to a small size (perhaps to a singularity) and the escape velocity becomes so great light cannot escape. The boundary of the black hole is called the event horizon because any event that occurs inside is invisible to outside observers. The radius of the black hole R_s is the Schwarzschild radius.

Although Schwarzschild's work was highly mathematical, his conclusion is quite simple. The Schwarzschild radius (in meters) depends only on the mass of the object (in kilograms):

$$R_s = \frac{2GM}{c^2}$$

In this simple formula, G is the gravitational constant, M is the mass, and c is the speed of light. A bit of arithmetic shows that a 1-solar-mass black hole has a Schwarzschild radius of 3 km, a 10-solar-mass black hole has a Schwarzschild radius of 30 km, and so on (■ Table 14-1). Even a very massive black hole would not have a very large event horizon.

Every object has a Schwarzschild radius determined by its mass, but not every object is a black hole. For example, Earth has a Schwarzschild radius of about 1 cm, meaning that it could become a black hole if you squeezed it inside that radius. Fortunately, Earth will not collapse spontaneously to become a black hole because the strength of the rock and metal in its interior is sufficient to support its weight. Only exhausted stellar cores more massive than about 3 solar masses can form black holes under the sole influence of their own gravity.

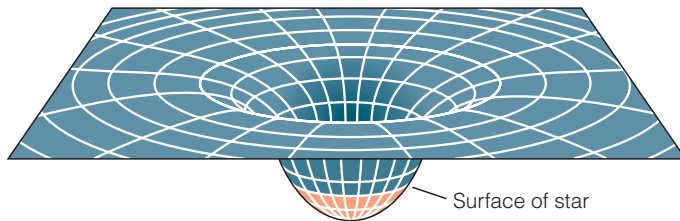
It is a **Common Misconception** to think of black holes as giant vacuum cleaners that will eventually suck in everything in the universe. A black hole is just a gravitational field, and at a reasonably large distance its gravity is no greater than that of a normal object of similar mass. If the sun were replaced by a 1-solar-mass black hole, the orbits of the planets would not change at all. ■ Figure 14-14 illustrates this by representing gravitational fields as curvature of the fabric of space-time. Normal, uncurved space-time is represented by a flat plane, and the presence of a mass such as a star curves the plane to produce a depression. The extreme curvature around a black hole produces a deep funnel-shaped surface in this graphic representation. You can see from the graphs that the gravity of a black hole becomes extreme only when you approach close to it.

Now you can check off another **Common Misconception** that may strike you as silly. Because of special effects in movies and TV, some people think black holes should actually look like funnels. Of course, the graphs of the strength of gravity around black holes look like funnels, but black holes themselves are not shaped like funnels. If you could approach a black hole,

■ **Table 14-1** | **The Schwarzschild Radius**

	Mass (M_\odot)	Radius
Star	10	30 km
Star	3	9 km
Star	2	6 km
Sun	1	3 km
Earth	0.000003	0.9 cm

Gravitational field around
a 5-solar-mass star



■ **Figure 14-14**

If you fell into the gravitational field of a star, you would hit the star's surface before you fell very far. Because a black hole is so small, you could fall much deeper into its gravitational field and eventually cross the event horizon. At a distance, the two gravitational fields are the same.

you might be able to see hot gas swirling inward, but you wouldn't be able to see the black hole itself.

Leaping into a Black Hole

Before you can search for real black holes, you must understand what theory predicts about a black hole. To explore that idea, you can imagine leaping, feet first, into a Schwarzschild black hole.

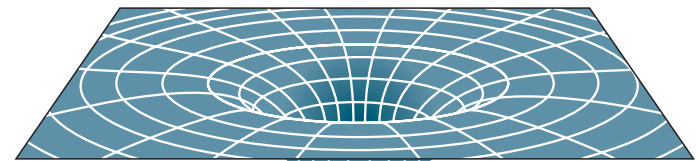
If you were to leap into a black hole of a few solar masses from a distance of 1 AU, the gravitational pull would not be very large, and you would fall slowly at first. Of course, the longer you fell and the closer you came to the center, the faster you would travel. Your wristwatch would tell you that you fell for about two months by the time you reached the event horizon.

Your friends who stayed behind would see something different. They would see you falling more and more slowly as you came closer to the event horizon because, as explained by general relativity, time slows down in curved space-time. This is known as **time dilation**. In fact, your friends would never actually see you cross the event horizon. To them you would fall more and more slowly until you seemed hardly to move. Generations later, your descendants could focus their telescopes on you and see you still inching closer to the event horizon. You, however, would have sensed no slowdown and would conclude that you had reached the event horizon after about two months.

Another relativistic effect would make it difficult to see you with normal telescopes. As light travels out of a gravitational field, it loses energy, and its wavelength grows longer. This is known as the **gravitational redshift**. Although you would notice no effect as you fell toward the black hole, your friends would need to observe at longer and longer wavelengths to detect you.

While these relativistic effects seem merely peculiar, other effects would be quite unpleasant. If you were falling feet first, you would feel your feet, which would be closer to the black hole, being pulled in more strongly than your head. This is a tidal force, and at first it would be minor. But as you got closer to the black hole, the tidal force would become very large. Another

Gravitational field around
a 5-solar-mass black hole



tidal force would compress you as both your left and your right side fell toward the center of the black hole. For any black hole with a mass like that of a star, the tidal forces would crush you sideways and stretch you lengthwise long before you reached the event horizon (■ Figure 14-15). The friction from such severe distortions of your body would heat you to millions of degrees, and you would emit X-rays and gamma rays. (Needless to say, this would render you inoperative as a thoughtful observer.)

Some years ago a popular book suggested that you could travel through the universe by jumping into a black hole in one place and popping out of another somewhere far across space. That might make for good science fiction, but tidal forces would make it an unpopular form of transportation even if it worked. You would certainly lose your luggage.

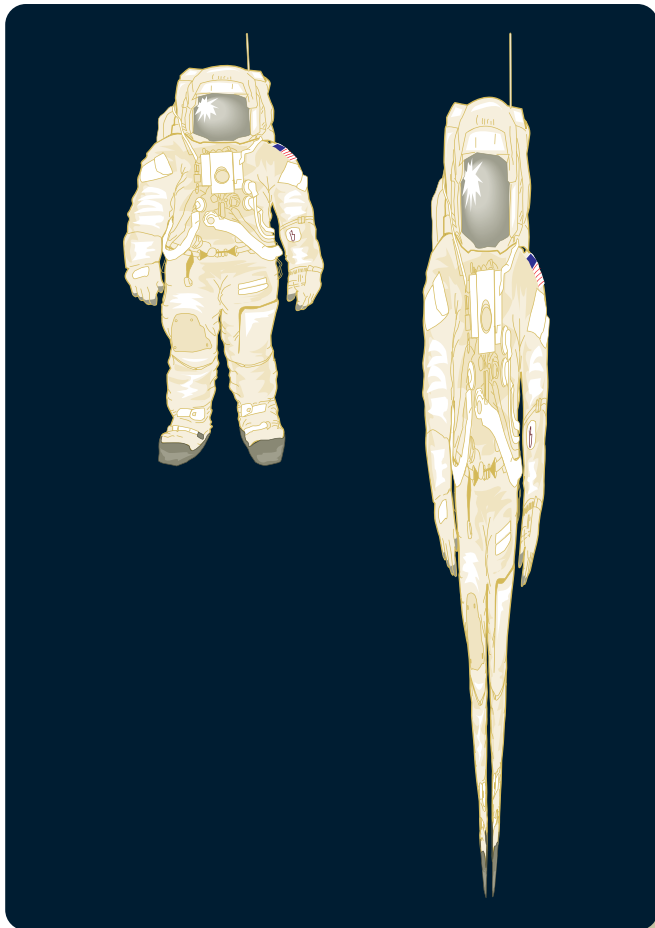
Your imaginary leap into a black hole is not frivolous. You now know how to find a black hole: Look for a strong source of X-rays. It may be a black hole into which matter is falling.

The Search for Black Holes

Do black holes really exist? The first X-ray telescopes reached orbit in the 1970s, and that allowed astronomers to begin searching for evidence of black holes. They tried to find one or more objects that were obviously black holes. That very difficult search is a good illustration of how the unwritten rules of science help scientists understand nature (**How Do We Know? 14-1**).

A black hole alone is totally invisible because nothing can escape from its event horizon, but if matter flows into a black hole, it will whirl through an accretion disk and become hot enough to emit X-rays before it reaches the event horizon. An isolated black hole in space will not have much matter flowing into it, but a black hole in a binary system might receive a steady flow of matter transferred from the companion star. This suggests you can search for black holes by looking closely at X-ray binaries.

Some X-ray binaries such as Hercules X-1 contain a neutron star, and they will emit X-rays much as would a binary containing a black hole. You can tell the difference in two ways. If the



■ **Figure 14-15**

Leaping feet first into a black hole. A person of normal proportions (left) would be distorted by tidal forces (right) long before reaching the event horizon around a typical black hole of stellar mass. Tidal forces would stretch the body lengthwise while compressing it laterally. Friction from this distortion would heat the body to high temperatures.

compact object emits pulses, you know it is a neutron star because the neutron star has a solid surface relative to which hot spots and beams are anchored and spin into and out of Earth's view. With no solid surface, a black hole would not be able to emit an extended series of regular pulses. Another clue depends on the mass of the object. If the mass of the compact object is greater than about 3 solar masses, it cannot be a neutron star; it must be a black hole.

■ **Figure 14-16**

The X-ray source Cygnus X-1 consists of a supergiant B0 star and a compact object orbiting each other. Gas from the B0 star's stellar wind flows into the hot accretion disk around the compact object, and the X-rays astronomers detect come from the disk. (Don Dixon/cosmographica.com)

The first X-ray binary suspected of harboring a black hole was Cygnus X-1, the first X-ray object discovered in the constellation Cygnus. It contains a supergiant B0 star and a compact object orbiting each other with a period of 5.6 days. Astronomers suspected that the X-rays were emitted by matter from the star flowing into the compact object. The object is invisible, but Doppler shifts in the spectrum reveal the motion of the B0 star around the center of mass of the binary. From the geometry of the orbit, astronomers were able to calculate that the mass of the compact object had to be greater than 3.8 solar masses, well above the maximum for a neutron star.

To confirm that black holes existed, astronomers needed a conclusive example, an object that couldn't be anything else. Cygnus X-1 didn't quite pass that test when it was first discovered. Perhaps the B0 star was not a normal star and its portion of the system mass was incorrectly estimated, or perhaps the system contained a third star. Either possibility would distort the analysis. At the time, astronomers could not conclusively show that Cygnus X-1 contained a black hole.

It took years of work to understand Cygnus X-1. Further observations and analysis show that the star has a mass of about 25 solar masses, and the compact object is about 10 times the mass of the sun. Astronomers conclude that matter flows from the B0 star as a strong stellar wind, and much of that matter gets caught in a hot accretion disk about five times larger in diameter than the orbit of Earth's moon. The inner few hundred kilometers of the disk has a temperature of about 2 million Kelvin—hot enough to radiate X-rays (■ Figure 14-16). The evidence is now strong that Cyg X-1 contains a black hole.

As X-ray telescopes have found many more X-ray-emitting objects, the list of black hole candidates has grown to dozens. A few of these objects are shown in ■ Table 14-2. Each candidate is a compact object surrounded by a hot accretion disk in a close X-ray binary system. Some of the binary systems are easier to



Checks on Fraud in Science

How do you know scientists aren't just making stuff up? The unwritten rules of science make fraud difficult, and the way scientists publish their research makes it almost impossible. Scientists depend on each other to be honest, but they also double-check everything.

For example, all across North America, black-capped chickadees sing the same quick song. Some people say it sounds like *Chick-a-dee-dee-dee*, but others say it sounds like *Hey-sweetie-sweetie-sweetie*. You could invent tables of data and publish a paper reporting that you had recorded chickadees around Ash Lake in northern Minnesota that sing a backward song: *Sweetie-sweetie-sweetie-hey*. Experts of brain development and animal learning would be amazed, and your research might secure you praise from your colleagues, a job offer at a prestigious university, or a generous grant—but only if you could get away with it.

The first step in your scheme would be to publish your results in a scientific journal. Because the journal's reputation rests on the accuracy of the papers it publishes, the editor sends all submitted papers to one or more experts for peer review. Those world experts on chickadees would almost certainly notice

things wrong with your made-up data tables. On their recommendation, the editor would probably refuse to publish your paper.

Even if your faked data fooled the peer reviewers, you would probably be found out once the paper was published. Experts on bird song would read your paper and flock to Ash Lake to study the bird songs themselves. By the next spring, you would be found out—and the journal would be forced to publish an embarrassing retraction of your article.

One of the rules of science is that good results must be repeatable. Scientists routinely repeat the work of others, not only to check the results but as a way to start a new research topic. When someone calls a news conference and announces a new discovery, other scientists begin asking, "How does this fit with other observations? Has this been checked? Has this been peer reviewed?" Until a result has been published in a peer-reviewed journal, scientists treat it with extra care. Fraud isn't unheard of in science. But because of peer review and the requirement of repeatability in science, bad research, whether the result of carelessness or fraud, is usually exposed quickly.



Chickadees always sing the same song. Hey-Sweetie-Sweetie-Sweetie. (Steve and Dave Maslowski/Photo Researchers, Inc.)

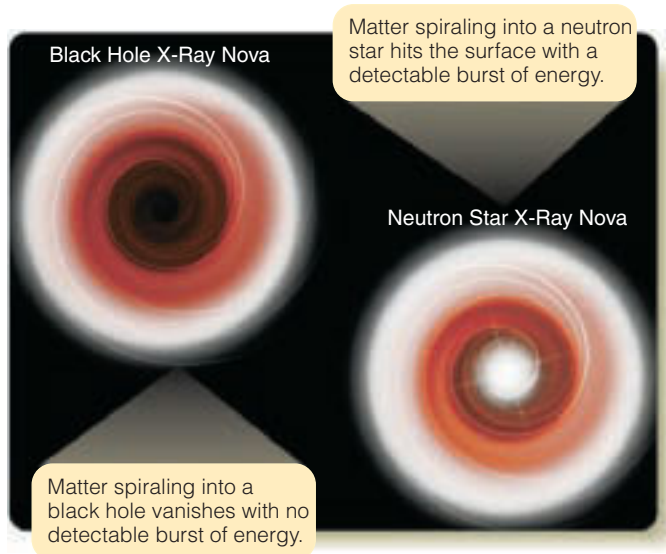
Table 14-2 | Nine Black Hole Candidates

Object	Location	Companion Star	Orbital Period	Mass of Compact Object
Cygnus X-1	Cygnus	B0 supergiant	5.6 days	10 M_{\odot}
LMC X-3	Dorado	B3 main-sequence	1.7 days	~10 M_{\odot}
A0620-00	Monocerotis	K main-sequence	7.75 hours	10 \pm 5 M_{\odot}
V404 Cygni	Cygnus	K main-sequence	6.47 days	12 \pm 2 M_{\odot}
GRO J1655-40	Scorpius	F-G main-sequence	2.61 days	6.9 \pm 1 M_{\odot}
QZ Vul	Vulpecula	K main-sequence	8 hours	10 \pm 4 M_{\odot}
4U 1543-47	Lupus	A main-sequence	1.123 days	2.7–7.5 M_{\odot}
V4641 Sgr	Sagittarius	B supergiant	2.81678 days	8.7–11.7 M_{\odot}
XTEJ1118+480	Ursa Major	K main-sequence	0.170113 days	>6 M_{\odot}

analyze than others, but, in the end, it has become clear that at least some of these compact objects are clearly too massive to be neutron stars and must be black holes. The evidence is now overwhelming: Black holes really do exist.

Another way to confirm that black holes are real is to search for evidence of their distinguishing characteristic—event horizons—and that search too has been successful. In one study, astronomers

selected 12 X-ray binary systems, six of which seemed to contain neutron stars and six of which were thought to contain black holes. Using X-ray telescopes, the astronomers monitored the systems, watching for telltale flares of energy as blobs of matter fell into the accretion disks and spiraled inward. In the six systems thought to contain neutron stars, the astronomers could detect final bursts of energy when the blobs of matter finally impacted the surfaces of the



■ **Figure 14-17**

Gas spiraling into an accretion disk grows hot; and, as it nears the central object, a strong gravitational redshift makes it appear redder and dimmer. Systems containing a neutron star emit bursts of energy when the gas hits the surface of the neutron star, but such bursts are not seen for systems containing black holes. In those systems, the matter vanishes as it approaches the event horizon. This is direct observational evidence of an event horizon around black holes. (NASA/CXC/SAO)

neutron stars. In the six systems suspected of containing black holes, however, the blobs of matter spiraled inward through the accretion disks and vanished without final bursts of energy. Evidently, those blobs of matter had vanished as they approached the event horizons (■ Figure 14-17). This is dramatic evidence that event horizons are real.

The evidence shows that black holes really do exist. The problem now is to understand how these objects interact with the matter flowing into them through accretion disks to produce high-energy jets and outbursts.

SCIENTIFIC ARGUMENT

If relativistic effects slow time and prevent you from seeing matter cross the event horizon, how can infalling matter disappear without a trace?

This argument brings together observations and theory. Astronomers observed flares when matter hit the surfaces of neutron stars, but observed no flares when matter fell into a black hole. Although time slows near the event horizon, remember the gravitational redshift. Hot matter flowing into a black hole can emit X-rays, but as the matter nears the event horizon, the gravitational redshift lengthens the wavelengths dramatically. The matter vanishes, not because you see it cross the event horizon but because its photons are shifted to undetectably long wavelengths.

Now build a new argument to review a basic principle. **Why does matter become hot as it falls into a black hole?**

14-3 Compact Objects with Disks and Jets

MATTER FLOWING INTO A NEUTRON STAR or a black hole forms an accretion disk, and that can produce some surprising phenomena. Astronomers are just beginning to understand these peculiar effects.

Jets of Energy from Compact Objects

Observations show that some compact objects are emitting jets of gas and radiation in opposite directions. These jets are similar to the bipolar outflows ejected by protostars but much more powerful. You have seen in the X-ray images on page 285 that some young pulsars, including the Crab Nebula pulsar, are ejecting jets of highly excited gas. The Vela pulsar does the same (Figure 14-4). Systems containing black holes can also eject jets. The black hole candidate GRO J1655-40 has been observed at radio wavelengths sporadically ejecting oppositely directed jets at 92 percent the speed of light.

One of the most powerful examples of this process is an X-ray binary called SS 433. Its optical spectrum shows sets of spectral lines that are Doppler shifted by about one-fourth the speed of light, with one set shifted to the red and one set shifted to the blue. Furthermore, the two sets of lines shift back and forth across each other with a period of 164 days. At the time of its discovery, news media reported, with a smirk, that astronomers had discovered an object that was both approaching and receding at a fantastic speed, but astronomers recognized the Doppler shifts as evidence of oppositely directed jets.

Apparently, SS 433 is a binary system in which a compact object (probably a black hole) pulls matter from its companion star and forms an extremely hot accretion disk. Jets of high-temperature gas blast away from the disk in beams aimed in opposite directions. As the disk precesses, it sweeps these beams around the sky once every 164 days, and telescopes on Earth detect light from gas carried outward in both beams. One beam produces a redshift, and the other produces a blueshift.

It's not clear how an accretion disk can produce jets. Accretion disks around neutron stars and black holes are very small, spin very fast, and grow very hot. Somehow the hot gas in the disk can emit powerful beams of gas and radiation along the disk's axis of rotation (■ Figure 14-18). The exact process isn't well understood, but it seems to involve magnetic fields that get caught in the accretion disk and are twisted into tightly wound tubes that squirt gas and radiation out of the disk and confine it in narrow beams. You can recognize the geometry of SS 433 in Figure 14-18.

Such pairs of jets are a prototype that illustrates how the gravitational field around a compact object can produce powerful beams of radiation and matter. You will meet this phenomenon again in a later chapter when you study peculiar galaxies.



■ **Figure 14-18**

In this artist's impression, matter from a normal star flows into an accretion disk around a compact object. Processes in the spinning disk eject gas and radiation in jets perpendicular to the disk. (© 2005, Fahad Sulehria, www.novacelestia.com)

Gamma-Ray Bursts

The Cold War plays a minor part in the story of neutron stars and black holes. In 1963, a nuclear test ban treaty was signed, and by 1968, the United States was able to put a series of satellites in orbit to watch for nuclear tests that were violations of the treaty. A nuclear detonation emits gamma rays, so the satellites were designed to watch for bursts of gamma rays coming from Earth. The experts were startled when the satellites detected about one gamma-ray burst a day coming from space. When those data were finally declassified in 1973, astronomers realized that the bursts might be coming from neutron stars and black holes. These bursts are now known as **gamma-ray bursts** (abbreviated **GRBs**).

The Compton Gamma Ray Observatory reached orbit in 1991 and immediately began detecting gamma-ray bursts at the rate of a few a day. Its observations showed that the intensity of the gamma rays rises to a maximum in seconds and then fades away quickly; a burst is usually over in a few seconds to a minute. Data from the Compton Observatory also showed that the gamma-ray bursts were coming from all over the sky and not from any particular region. This helped astronomers eliminate some hypotheses.

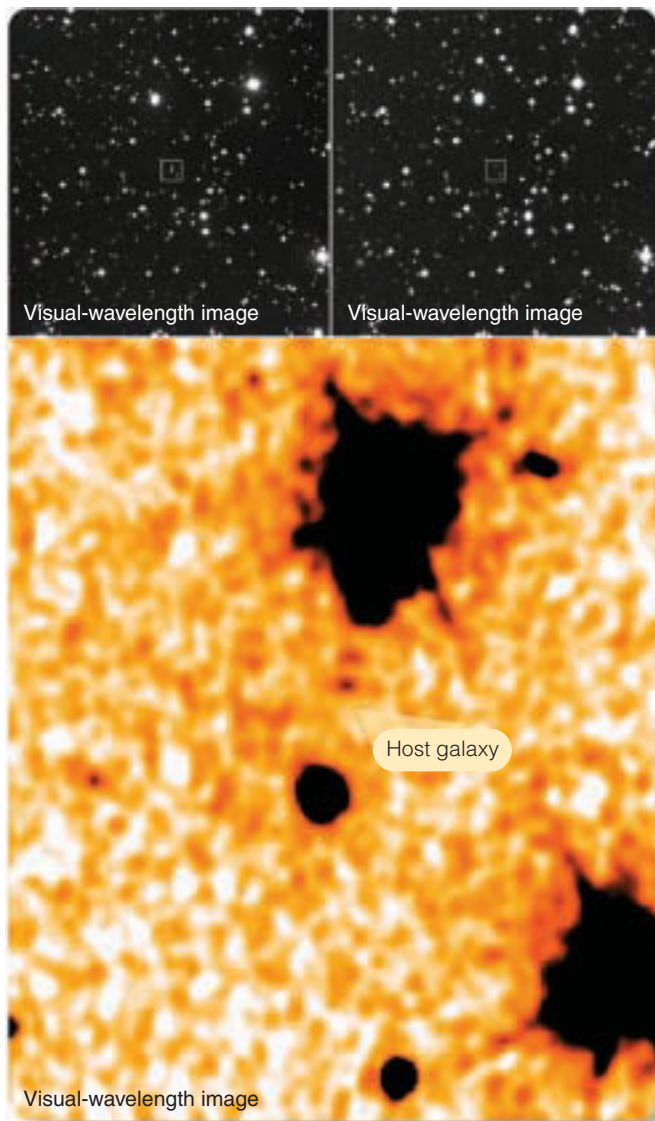
For example, there was a hypothesis that the gamma-ray bursts were being produced by relatively common events involving the stars in our galaxy, but the results from the Compton Observatory eliminated that possibility. If the gamma-ray bursts were produced among stars in our galaxy, you would expect to

see them most often along the Milky Way where there are lots of stars. That the bursts occurred all over the sky meant that they were being produced by rare events in distant galaxies.

Gamma-ray bursts are hard to study because they occur without warning and fade so quickly; but, starting in 1997, new satellites in orbit were able to detect gamma-ray bursts. Such studies showed that there are two kinds of gamma-ray bursts. Short bursts last less than 2 seconds, but longer bursts can go on for many seconds. Specialized satellites can detect bursts, quickly determine their location in the sky, and immediately alert astronomers on the ground. When telescopes on Earth swiveled to image the locations of the bursts, they detected fading glows that resembled supernovae (■ Figure 14-19), suggesting that long gamma-ray bursts are produced by a certain kind of supernova explosion.

Theory proposes that a star more massive than some upper limit of about 20 solar masses can exhaust its nuclear fuel and collapse directly into a black hole. Models show that the collapsing star would conserve angular momentum and spin very rapidly, slowing the collapse of the equatorial parts of the star. The poles of the star would fall in quickly, and that would focus beams of intense radiation and ejected gas that would blast out along the axis of rotation. Such an eruption has been called a **hypernova** (■ Figure 14-20). If one of those beams were pointed at Earth, it could produce a powerful gamma-ray burst. Evidently the long gamma-ray bursts are produced by hypernovae.

Short gamma-ray bursts don't seem to be associated with hypernovae. Some repeat, and these repeating bursts seem to be produced by neutron stars with magnetic fields 100 times stronger than that in a normal neutron star. Dubbed **magnetars**, these objects can produce bursts of gamma rays when shifts in the



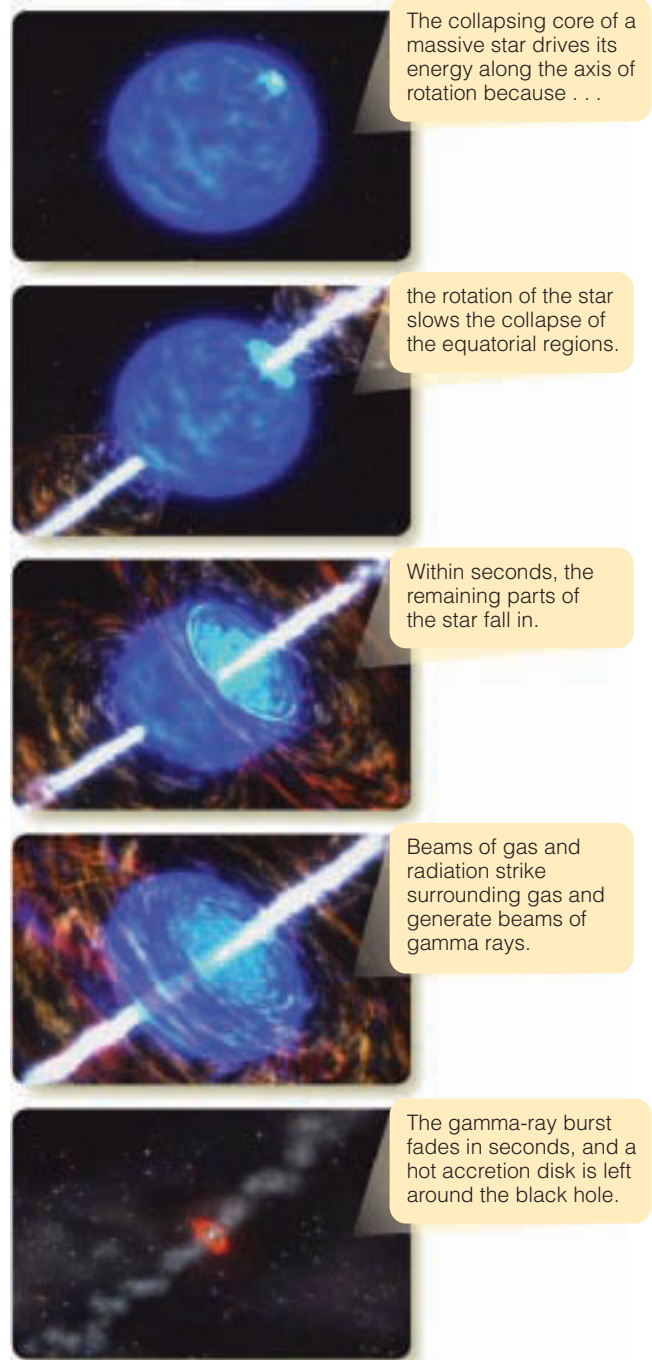
■ **Figure 14-19**

Alerted by gamma-ray detectors on satellites, observers used one of the VLT 8.2-meter telescopes on a mountaintop in Chile to image the location of a gamma-ray burst only hours after the burst. The image at top left shows the fading glow of the eruption. The image at top right, recorded 13 years before, reveals no trace of an object at the location of the gamma-ray burst. The Hubble Space Telescope image at bottom was recorded a year later and reveals a very faint galaxy at the location of the gamma-ray burst. (ESO and NASA)

magnetic field break the crust of the neutron stars—causing “starquakes”—and release large amounts of energy (■ Figure 14-21). One of those objects produced a burst of gamma rays that reached Earth in 1998 and was strong enough to temporarily ionize Earth’s upper atmosphere, disrupting radio communication worldwide.

Eruptions on the surfaces of magnetars may be common. Changes in the Cassiopeia A supernova remnant (Figure 13-17) appear to have been caused by an eruption on the central neutron star that occurred about 1953. The Fermi Gamma-Ray

A Hypernova Explosion

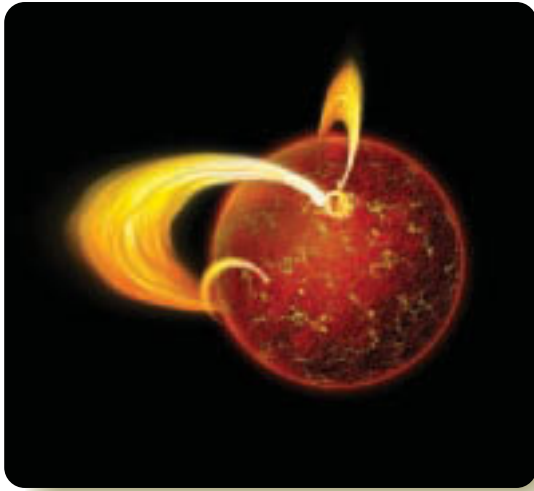


■ **Figure 14-20**

The collapse of the cores of extremely massive stars can produce hypernova explosions, which are thought to be the source of gamma-ray bursts longer than 2 seconds. (NASA/Skyworks Digital)

Space Telescope in orbit has detected a neutron star producing rapid-fire eruptions as often as 100 times in 20 minutes. Such eruptions also are thought to be somehow related to starquakes in the crusts of magnetars.

Not all short gamma-ray bursts are produced by magnetars. Some bursts have occurred in parts of distant galaxies where you



■ **Figure 14-21**

Some neutron stars appear to have magnetic fields up to 1000 times stronger than those in a normal neutron star. These magnetars can produce bursts of gamma rays when shifts in the magnetic field rupture the rigid crust of the neutron star. (NASA/CXC/M. Weiss)

would not expect to find the young, massive stars that produce magnetars or hypernovae, and the afterglows don't resemble fading supernovae. These bursts may be produced by the merger of two neutron stars that orbited around each other, radiated orbital energy as gravitational radiation, and spiraled into each other. Such a merger would produce a violent explosion as the two neutron stars merged to form a black hole.

Other short gamma-ray bursts are probably produced by the merger of a neutron star and a black hole. As these objects spiral into each other, the neutron star is ripped apart and swallowed by the black hole. That could produce a gamma-ray burst, but the burst and its fading afterglow should be different from that produced by the merger of two neutron stars. Astronomers are

now working to distinguish between these two kinds of short gamma-ray bursts.

In 2008 the Swift orbiting telescope detected an intense gamma-ray burst that originated in a galaxy 7.5 billion light years from Earth. The burst was so powerful that for about one minute, its visual-wavelength component was bright enough to see with the unaided eye. If you had been looking directly at it, you would have seen it appear as a star slightly brighter than those in the Little Dipper. Another powerful gamma-ray burst detected by Swift in 2008 originated in a galaxy 12.2 billion light-years away. In spite of the distance, it was one of the brightest gamma-ray bursts ever detected. Astronomers suspect that these bursts were produced by hypernova collapses of massive stars in which one of the jets was aimed directly at Earth.

Could a gamma-ray burst occur near Earth? The nearest known binary pulsar is only about 2000 ly from Earth. If a gamma-ray burst occurred at that distance, the gamma rays would shower Earth with radiation equivalent to a 10,000-megaton nuclear blast, equivalent to a full-scale nuclear war between superpowers. (The largest single bombs ever made were a few tens of megatons.) The gamma rays could create enough nitric oxide in the atmosphere to produce intense acid rain and also would destroy the ozone layer, exposing life on Earth to deadly levels of solar ultraviolet radiation. Gamma-ray bursts can occur relatively near the Earth as often as every few hundred million years and could be one of the causes of the mass extinctions that show up in the fossil record.

Does it surprise you that such astonishing events as merging neutron stars and hypernovae produce something so common that gamma-ray telescopes observe one or more every day? Remember that these events are so powerful they can be detected over very great distances. There may be 30,000 neutron star binaries in each galaxy, and there are billions of galaxies within range of gamma-ray telescopes. Earthlings are treated to the entire observable universe's display of these cosmic catastrophes.

What Are We? Abnormal

Look around. What do you see? A table, a chair, a tree? It's all normal stuff. The world we live in is familiar and comfortable, but astronomy reveals that "normal" isn't normal at all. The universe is, for the most part, utterly unlike anything you have ever experienced.

Throughout the universe, gravity makes clouds of gas form stars, and in turn the stars generate energy through nuclear fusion in their cores, which delays gravity's final

victory. But gravity always wins. You have learned that stars of different masses die in different ways, but you have also discovered that they always reach one of three end states: white dwarfs, neutron stars, or black holes. However strange these compact objects are, they are common. They are normal.

The physics of compact objects is extreme and violent. You are not accustomed to objects as hot as the surface of a

neutron star, and you have never experienced the environment near a black hole, where gravity is so strong it would pull you to pieces.

The universe is filled with things that are so violent and so peculiar they are almost unimaginable, but they are so common they deserve the label "normal." Next time you are out for a walk, look around and notice how beautiful Earth is and recall how unusual it is compared to the rest of the universe.

Study and Review

Summary

- ▶ When a supernova explodes, the core collapses to very small size. Theory predicts that the collapsing core cannot support itself as a white dwarf if its mass is greater than 1.4 solar masses, the Chandrasekhar limit. If its mass lies between 1.4 solar masses and about 3 solar masses, it can halt its contraction and form a **neutron star (p. 280)**.
- ▶ A neutron star is supported by the pressure of the degenerate neutrons. Theory predicts that a neutron star should be about 10 km in radius, spin very fast because it conserves angular momentum as it contracts, and have a powerful magnetic field.
- ▶ **Pulsars (p. 282)**, rapidly pulsing radio sources, were discovered in 1967. The **lighthouse model (p. 282)** explains pulsars as spinning neutron stars that emit beams of radiation from their magnetic poles. As they spin, they sweep the beams around the sky like lighthouses; if the beams sweep over Earth, astronomers detect pulses. The short pulses and the discovery of a pulsar in the supernova remnant called the Crab Nebula were key evidence that pulsars are neutron stars.
- ▶ A spinning neutron star slows as it radiates its energy into space. Most of the energy emitted by a pulsar is carried away as a **pulsar wind (p. 282)**.
- ▶ Theory predicts that a neutron star cannot have a mass greater than about 3 solar masses. Dozens of pulsars have been found in binary systems, and those objects allow astronomers to estimate the masses of the neutron stars. Such masses are consistent with the predicted masses of neutron stars.
- ▶ Observations of the first binary containing two neutron stars revealed that the system is losing orbital energy by emitting **gravitational radiation (p. 286)**.
- ▶ In some binary systems, mass flows into a hot accretion disk around the neutron star and causes the emission of X-rays. **X-ray bursters (p. 288)** are systems in which matter accumulates on the surface of the neutron star and explodes.
- ▶ The fastest pulsars, the **millisecond pulsars (p. 288)**, appear to be old pulsars that have been spun up to high speed by mass flowing from binary companions.
- ▶ Planets have been found orbiting at least one neutron star. They may be the remains of a companion star that was mostly devoured by the neutron star, or they may have formed from a ring of gas and dust left orbiting the neutron star after the supernova explosion.
- ▶ If the collapsing core of a supernova has a mass greater than 3 solar masses, then it must contract to a very small size—perhaps to a **singularity (p. 291)**, an object of zero radius. Near such an object, gravity is so strong that not even light can escape, and the region is called a **black hole (p. 291)**.
- ▶ The outer boundary of a black hole is the **event horizon (p. 292)**; no event inside is detectable. The radius of the event horizon is the **Schwarzschild radius, R_s (p. 292)**, amounting to only a few kilometers for a black hole of stellar mass.
- ▶ If you were to leap into a black hole, your friends who stayed behind would see two relativistic effects. They would see your clock slow relative to their own clock because of **time dilation (p. 293)**. Also, they would see your light redshifted to longer wavelengths because of the **gravitational redshift (p. 293)**.
- ▶ You would not notice these effects, but you would feel powerful tidal forces that would deform and heat your mass until you grew hot enough to emit X-rays. Any X-rays you emitted before reaching the event horizon could escape.

- ▶ To search for black holes, astronomers must look for binary star systems in which mass flows into a compact object and emits X-rays. If the mass of the compact object is greater than about 3 solar masses, then the object is presumably a black hole. A number of such objects have been located.
- ▶ Clues that an X-ray source is caused by accretion into a black hole rather than onto a neutron star are lack of sustained regular pulsations and lack of flares when blobs of material in the accretion disk arrive at the central compact object.
- ▶ Black holes and neutron stars at the center of accretion disks can eject powerful jets of gas and radiation. Such jets have been detected.
- ▶ **Gamma-ray bursts (p. 297)** appear to be related to violent events involving neutron stars or black holes. Bursts longer than 2 seconds appear to arise during **hypernovae (p. 297)**, the collapse of massive stars to form black holes.
- ▶ Some short gamma-ray bursts are produced by shifts in the powerful magnetic fields in a type of pulsar called **magnetars (p. 297)**, whereas other bursts probably represent the merger of binary compact objects such as neutron-star pairs or neutron-star/black-hole pairs.

Review Questions

1. How are neutron stars and white dwarfs similar? How do they differ?
2. Why is there an upper limit to the mass of neutron stars?
3. Why do you expect neutron stars to spin rapidly?
4. If neutron stars are hot, why aren't they very luminous?
5. Why do you expect neutron stars to have a powerful magnetic field?
6. Why did astronomers conclude that pulsars actually could not be pulsating stars?
7. What does the short length of pulsar pulses tell you?
8. How does the lighthouse model explain pulsars?
9. What evidence can you cite that pulsars are neutron stars?
10. Why would astronomers naturally assume that the first discovered millisecond pulsar was relatively young?
11. How can a neutron star in a binary system generate X-rays?
12. If the sun has a Schwarzschild radius, why isn't it a black hole?
13. How can a black hole emit X-rays?
14. What evidence can you cite that black holes really exist?
15. How can mass transfer into a compact object produce jets of high-speed gas? X-ray bursts? Gamma-ray bursts?
16. Discuss the possible causes of gamma-ray bursts.
17. **How Do We Know?** How does peer review make fraud rare in science?

Discussion Questions

1. In your opinion, has the link between pulsars and neutron stars been sufficiently tested to be called a theory, or should it be called a hypothesis? What about the existence of black holes?
2. Why wouldn't an accretion disk orbiting a giant star get as hot as an accretion disk orbiting a compact object?

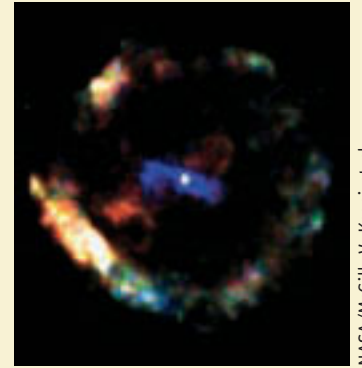
Problems

1. If a neutron star has a radius of 10 km and rotates 716 times a second, what is the speed of the surface at the neutron star's equator in terms of the speed of light?

2. Suppose that a neutron star has a radius of 10 km and a temperature of 1,000,000 K. How luminous is it? (*Hint:* See Chapter 9.)
3. A neutron star and a white dwarf have been found orbiting each other with a period of 11 minutes. If their masses are typical, what is their average separation? Compare the separation with the radius of the sun, 7×10^5 km. (*Hint:* See Chapter 9.)
4. If the accretion disk around a neutron star has a radius of 2×10^5 km, what is the orbital velocity of a particle at its outer edge? (*Hint:* Use circular velocity, Chapter 5.)
5. What is the escape velocity from the surface of a typical neutron star? How does that compare with the speed of light? (*Hint:* See Chapter 5.)
6. If Earth's moon were replaced by a typical neutron star, what would the angular diameter of the neutron star be as seen from Earth? (*Hint:* Use the small-angle formula, Chapter 3.)
7. If the inner accretion disk around a black hole has a temperature of 1,000,000 K, at what wavelength will it radiate the most energy? What part of the spectrum is this in? (*Hint:* Use Wien's law, Chapter 7.)
8. What is the orbital period of a bit of matter in an accretion disk 2×10^5 km from a 10-solar-mass black hole? (*Hint:* Use circular velocity, Chapter 5.)
9. If an X-ray binary consists of a 20-solar-mass star and a neutron star orbiting each other every 13.1 days, what is their average separation? (*Hint:* See Chapter 9.)

Learning to Look

1. The X-ray image at the right shows the supernova remnant G11.2–0.3 and its central pulsar in X-rays. The blue nebula near the pulsar is caused by the pulsar wind. How old do you think this system is? Discuss the appearance of this system a million years from now.

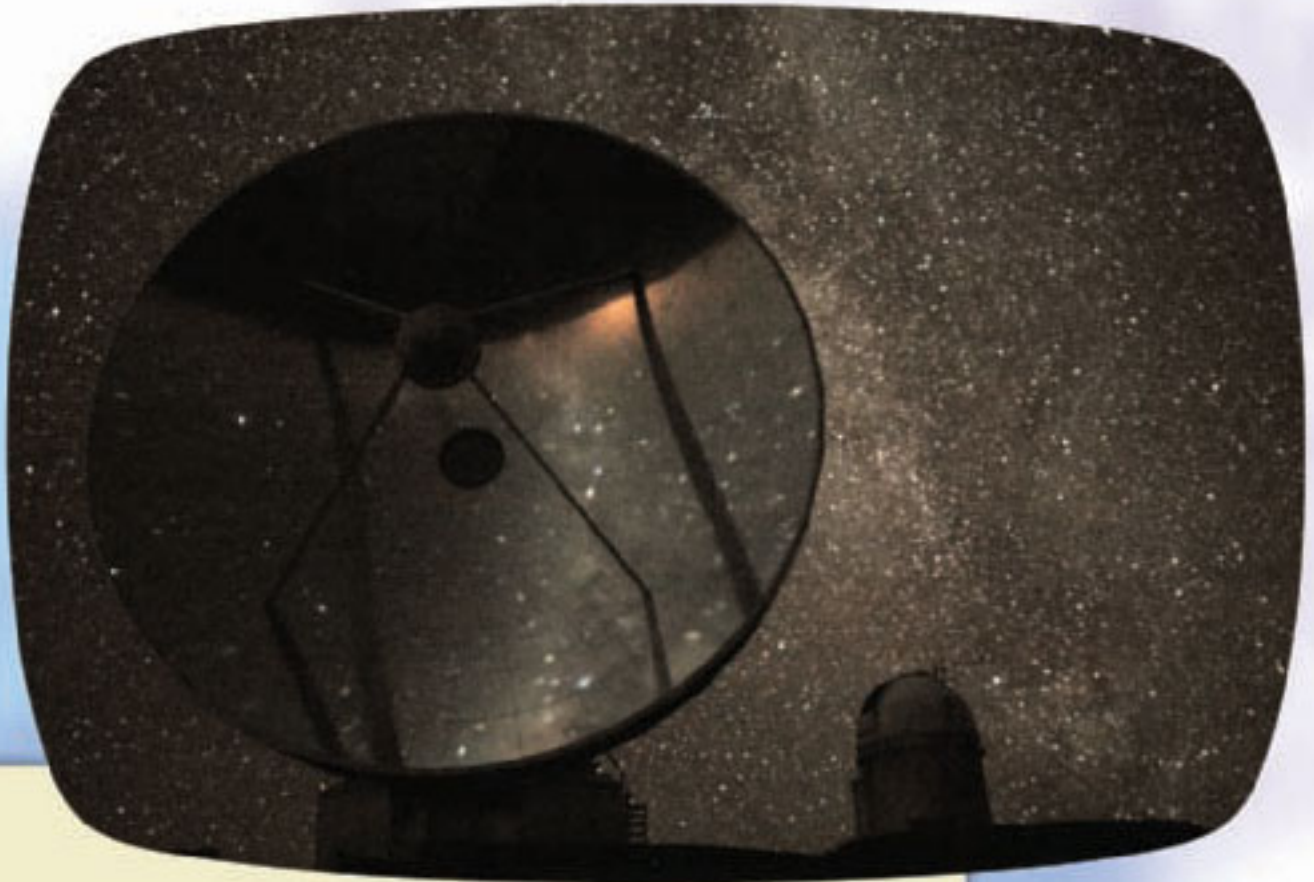


NASA/McGill, V. Kaspi et al.

2. What is happening in the artist's impression at the right? How would you distinguish between a neutron star and a black hole in such a system?



CXC/M. Weiss



Guidepost

You have traced the life stories of stars from their birth in clouds of gas and dust to their deaths as white dwarfs, neutron stars, or black holes. Now you are ready to step back and view stars in vast communities called galaxies. This chapter focuses on our home galaxy, the Milky Way, and addresses four essential questions:

— **How do you know that you live in a galaxy?**

— **How do you know that our Milky Way is a spiral galaxy, and what are the spiral arms?**

— **What lies at the center of the Milky Way Galaxy?**

— **How did the Milky Way Galaxy form and evolve?**

Discovering the Milky Way Galaxy by answering these questions will be one more step toward understanding the universe as a whole. In the chapters that follow, you will leave your home galaxy and voyage out among the billions of other galaxies that fill the depths of the universe.

The stars of our home galaxy, the Milky Way, rise behind a telescope dome and the highly polished surface of a submillimeter telescope at the La Silla European Southern Observatory in Chile. (ESO and Nico Housen)

THE STARS ARE YOURS is the title of a popular astronomy book written by James Pickering in 1948. The point of the title is that the stars belong to everyone equally, and you can enjoy the stars as if you owned them.

Next time you admire the night sky, recall that every star you see is part of the star system in which you live. You will learn in this chapter how evidence reveals that you are inside a great wheel of stars, a galaxy. The Milky Way Galaxy is over 80,000 ly in diameter and contains more than 100 billion stars. It is your galaxy because you live in it, but you are also a product of it, because the stars in the Milky Way Galaxy made many of the atoms in your body. You begin this chapter by pondering the notion that the stars belong to you, but when you reach the end of the chapter, you may realize that you also belong to the stars.

15-1 The Discovery of the Galaxy

IT SEEMS ODD to say that astronomers discovered something that is all around us, but it isn't obvious that we live in a galaxy. You might ask, "How do we know what our galaxy is like? Nobody has ever seen it from the outside." Because all scientific knowledge is based on evidence, you need to know a few facts about our galaxy to get started. The more interesting question is, how did astronomers come to know those facts? That story makes up one of the great adventures in astronomy.

The Great Star System

Since ancient times, humanity has been aware of a hazy band of light around the sky (■ Figure 15-1). The ancient Greeks named that band *galaxies kuklos*, the "milky circle." The Romans changed the name to *via lactia*, meaning "milky road" or "milky way." It was not until Galileo used his telescope in 1610 that anyone realized the Milky Way is made of a huge number of stars.

Almost every celestial object you can see with your unaided eyes is part of the Milky Way Galaxy. The only exception viewable from Earth's northern hemisphere is the Andromeda Galaxy (also known as Messier 31, abbreviated M31), which is barely visible as a faint patch of light in the constellation Andromeda.* As you will learn later in this chapter, our galaxy, if seen from a distance, would look similar to the Andromeda Galaxy (Figure 15-1b).

Galileo's telescope revealed that the glowing Milky Way is made up of stars, and later astronomers realized that the sun must

be located in a great wheel-shaped cloud of stars, which they called the star system. That star system appears, from our location inside it, as the band of the Milky Way you see encircling the sky. In 1750, Thomas Wright (1711–1786), drawing on the technology of the time, referred to the wheel-shaped star system as the grindstone universe, by analogy with the thick disks of stone used in mills. Wright used the term *universe* because, so far as was known at the time, the Milky Way star system was the entire universe.

The English astronomer Sir William Herschel (1738–1822) and his sister Caroline Herschel (1750–1848) set out to map the three-dimensional distribution of stars in the Milky Way. They assumed that they could see to the outer boundaries of the Milky Way in all directions. They hypothesized that by counting the number of stars that were visible in different directions they could find the relative distances to the edges of the star distribution. If they saw many stars in one direction, they reasoned that the edge of the Milky Way in that direction is far away. If their telescope revealed fewer stars in another direction, they concluded that edge must be closer. Calling their method "star gauging," they counted stars in 683 directions in the sky and outlined a model of the star system. Their data indicated that the stars were arranged in a disk shape with the sun near the center, apparently confirming the "grindstone model" (■ Figure 15-2). In some directions the Herschels saw very few stars, and these "holes in the sky" produced great irregularities along the edge of their diagram, as shown in Figure 15-2.

The model proposed by the Herschels was widely accepted and studied by other astronomers. The Herschels were not able to measure the size of the star system, but later astronomers attempted to do so by various means. Those efforts culminated with the early-20th-century work of Jacobus Kapteyn (1851–1922), who made a comprehensive analysis of the magnitudes, numbers, and motions of Milky Way stars. Kapteyn concluded that the star system's disk is about 10 kiloparsecs in diameter and 2 kiloparsecs thick. A **kiloparsec (kpc)** is 1000 pc.

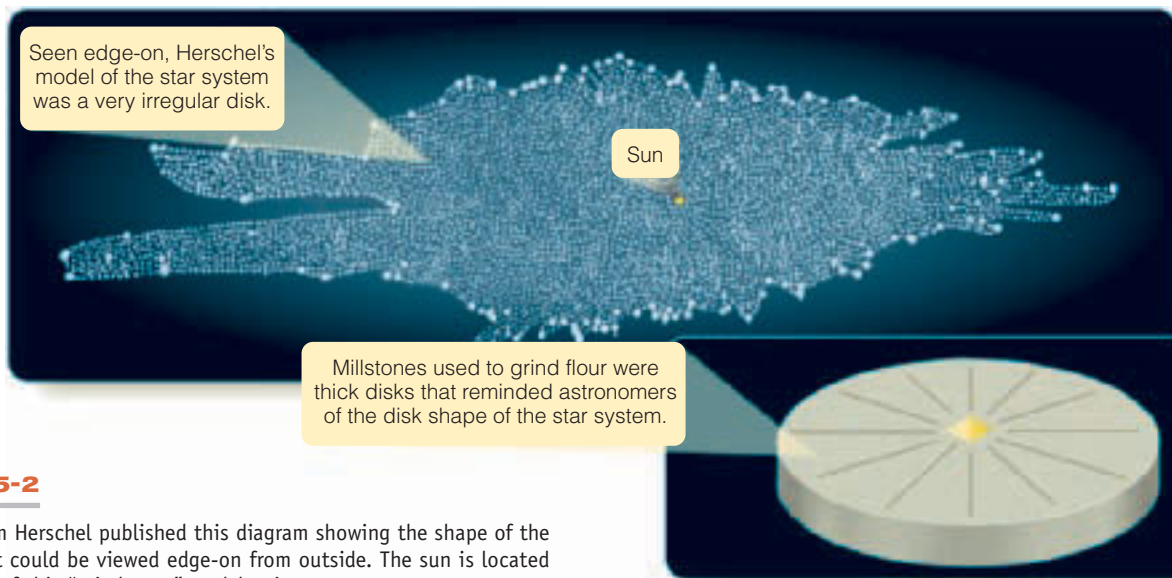
The Herschels assumed that they could see to the edge of the star system, but that was not correct. They were actually seeing only as far into the Milky Way as the interstellar dust permitted. At the time the Herschels did their work, astronomers did not understand that the interstellar medium blocks the passage of light (see Chapter 10). Because the Herschels counted roughly similar numbers of stars in most directions around the Milky Way, they incorrectly concluded that the sun is near the center of the star system. Furthermore, modern astronomers know that the "holes in the sky" observed by the Herschels are not empty but are actually especially dense interstellar clouds completely blocking the view of stars beyond them.

Imagine an analogous situation, with you standing in a crowd of people within a very dense fog. You might get the mistaken impression that the crowd extends only as far away as you can see in the fog. Your view reaches roughly the same distance in all directions, so you would think you were near the center of

*Consult the star charts at the end of this book to locate the Milky Way and the Andromeda Galaxy, labeled M31 on the chart.

■ **Figure 15-1**

(a) Nearby stars look bright, and people around the world group them into different constellations. Nevertheless, the vast majority of the stars in our galaxy merge into a faintly luminous path that circles the sky, the Milky Way. This artwork shows the location of a portion of the Milky Way near a few bright winter constellations. (See Figure 15-3 and the star charts at the end of this book to locate other sections of the Milky Way in your sky.) (b) This photograph of the Andromeda Galaxy, a spiral galaxy about 2.5 million ly from Earth, shows approximately what our galaxy would look like if you could view it from the same distance. (AURA/NOAO/NSF)



■ **Figure 15-2**

In 1785, William Herschel published this diagram showing the shape of the star system if it could be viewed edge-on from outside. The sun is located near the center of this "grindstone" model universe.

the crowd. The real size of the crowd, and the location of its true center, would be unknown to you. Modern astronomers know that the Milky Way Galaxy is much larger than Kapteyn estimated, and that the sun is not at its center. How the human race realized the truth about our location in the universe is an adventure that begins with a woman studying stars that pulsate and leads to a man studying distant star clusters.

Variable Stars and the Size of the Milky Way

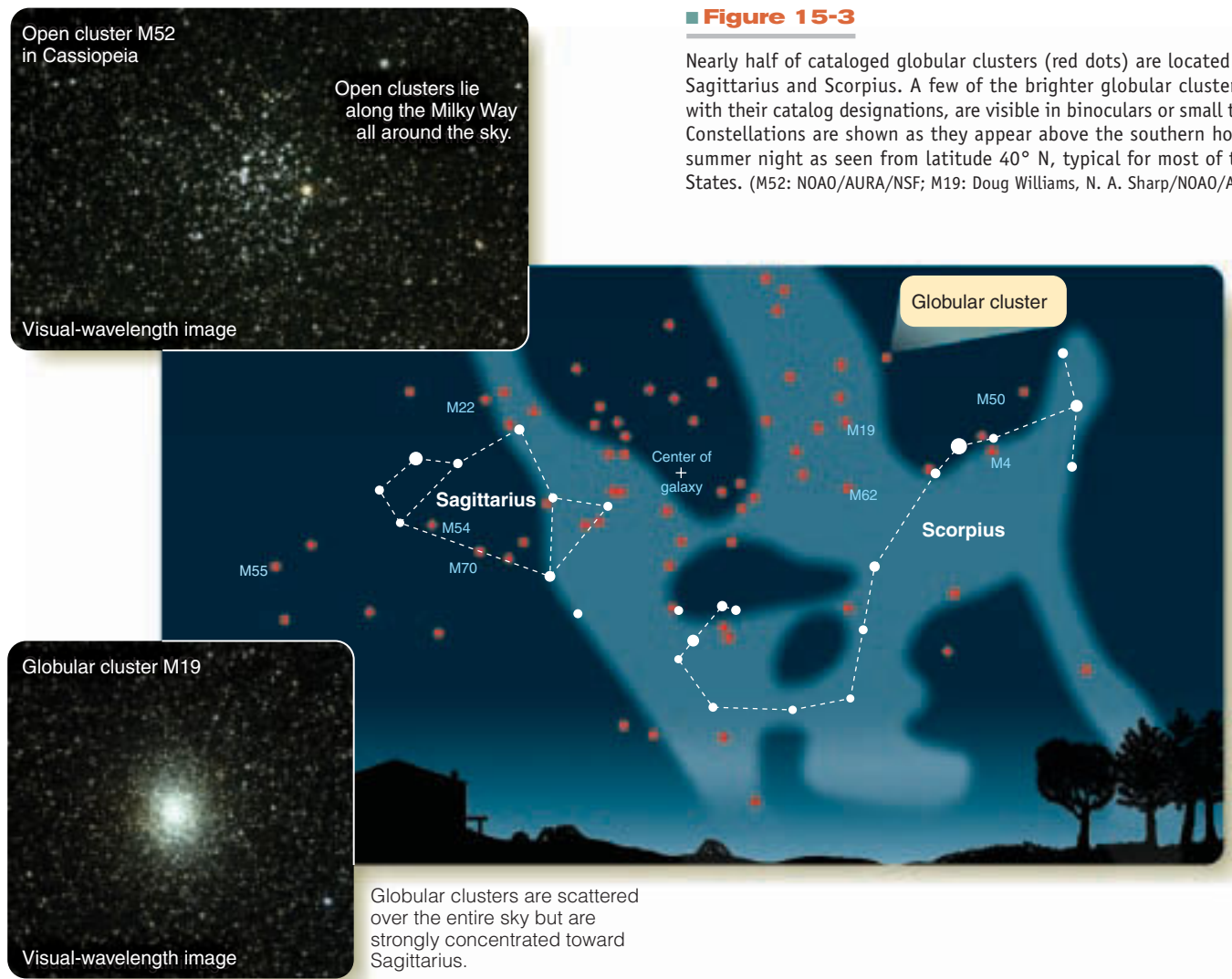
Until early in the 20th century no one knew that humanity lives inside a galaxy. That began to change around 1920 when an astronomer named Harlow Shapley (1885–1972) discovered how big our star system really is. Besides being one of the turning points of modern astronomy, Shapley’s study illustrates one of the most common techniques in astronomy. If you want to understand how astronomers know things about the universe, then Shapley’s story is worth tracing in detail.

You learned in Chapter 12 that star clusters come in two quite different types, open clusters and globular clusters (see page 246). Shapley began his research on the star system by noticing that, although open star clusters are scattered all along the Milky Way, more than half of all globular clusters lie in or near the constellation Sagittarius. The globular clusters seem to be distributed in a great cloud with a center located in the direction of Sagittarius (■ Figure 15-3). Shapley assumed that the orbital motion of these clusters is controlled by the gravitation of the entire star system, and, for that reason, he concluded that the center of the star system could not be near the sun but must lie somewhere toward Sagittarius.

To find the distance to the center of the star system and thus the size of the star system as a whole, Shapley needed to find the distance to the star clusters, but that was difficult to do. The clusters are much too far away to have measurable parallaxes. They do, however, contain variable stars (see Chapter 12), and those were the beacons Shapley needed to find the distances to the clusters.

■ **Figure 15-3**

Nearly half of cataloged globular clusters (red dots) are located in or near Sagittarius and Scorpius. A few of the brighter globular clusters, labeled with their catalog designations, are visible in binoculars or small telescopes. Constellations are shown as they appear above the southern horizon on a summer night as seen from latitude 40° N, typical for most of the United States. (M52: NOAO/AURA/NSF; M19: Doug Williams, N. A. Sharp/NOAO/AURA/NSF)



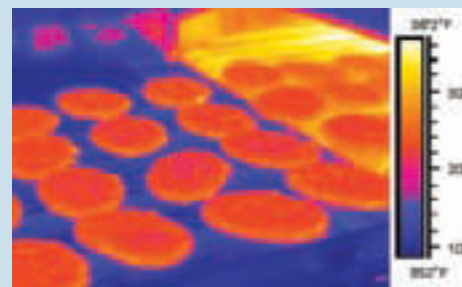
Calibration

How do you take the temperature of a vat of molten steel? Astronomers often say that Shapley “calibrated” the Cepheids for the determination of distance, meaning that he did all the detailed background work to determine the luminosities of Cepheids. After that, he and other astronomers could use his calibrated period–luminosity diagram to find the distance to other Cepheids without repeating the detailed calibration.

Calibration is actually very common in science because it saves a lot of time and effort. For example, engineers in steel mills must monitor the temperature of molten steel, but they can’t dip in a thermometer. Instead, they can use handheld devices that measure the color of molten steel. You recall from Chapter 7 that the color of blackbody radiation

is determined by its temperature. Molten steel emits visible and infrared radiation that is nearly perfect blackbody radiation, so the manufacturer can calibrate the engineer’s devices to convert the measured color to a temperature displayed on digital readouts. The engineers don’t have to repeat the calibration every time; they just point their instrument at the molten steel and read off the temperature. Astronomers have made the same kind of color–temperature calibration for stars.

As you read about any science, notice how calibrations are used to simplify common measurements. But notice, too, how important it is to get the calibration right. An error in calibration can throw off every measurement made with that calibration.



An infrared video camera calibrated to measure temperature allows bakers to monitor the operation of their ovens. (Courtesy of FLIR Systems, Inc.)

Shapley knew about the work of Henrietta Leavitt (1868–1921), who in 1912 had shown that a Cepheid variable star’s period of pulsation is related to its brightness. Leavitt worked on stars whose distances were unknown, so she was unable to find their absolute magnitudes (meaning their luminosities), but astronomers realized that the Cepheids could be a powerful tool in astronomy if their true luminosities could be discovered.

Cepheids are giant and supergiant stars and so are relatively rare. None lies close enough to Earth to have a measurable parallax, but their proper motions—slow movements across the sky—can be measured. The more distant a star is, the smaller its proper motion tends to be, so proper motions contain clues to distance. Ejnar Hertzsprung (co-inventor of the H–R diagram) made an early attempt to determine the absolute magnitudes of the Cepheids, but Shapley went further. He found 11 Cepheids with measured proper motions and used a statistical process to find their average distance and thus their average absolute magnitude. Then, he could erase Leavitt’s *apparent* magnitudes from the vertical axis of the period–luminosity diagram (see Figure 12-14) and write in *absolute* magnitudes, representing true luminosities. All of the stars in the diagram were thus **calibrated** as standard light sources that astronomers could use to find distances. Calibrations like this one are important tools in science (**How Do We Know? 15-1**).

Finding distances using Cepheid variable stars is so important in astronomy that you should pause to examine the process. Suppose you studied an open star cluster and discovered that it contained a type I Cepheid variable star with a period of 10 days and an average apparent magnitude of 10.5. How far away is the

cluster? Using the period–luminosity diagram (see Figure 12-14), you will find that the absolute magnitude of the star must be about -3 . Then the distance modulus (see Chapter 9) is:

$$m_V - M_V = 10.5 - (-3) = 13.5$$

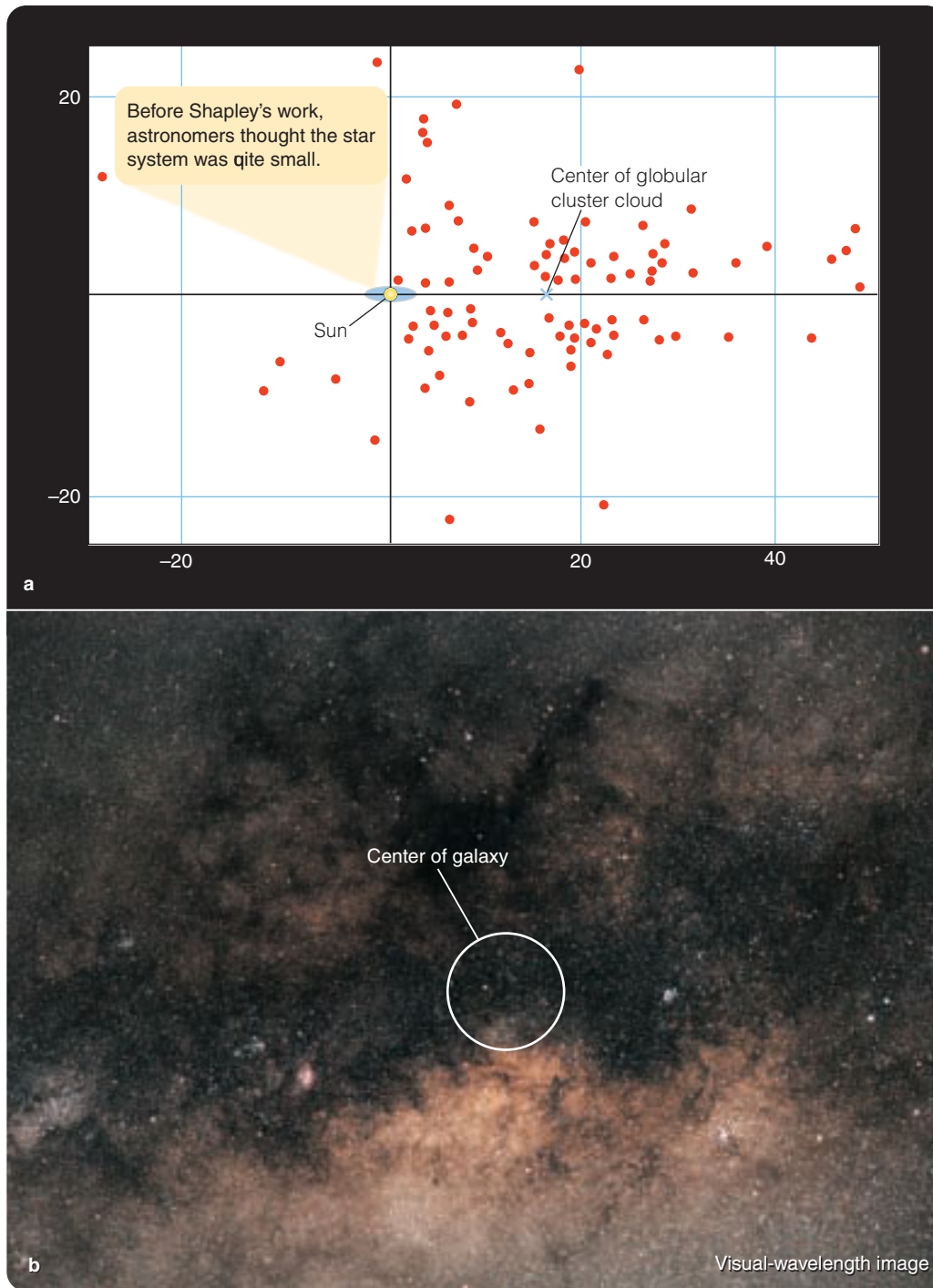
You can then solve the magnitude–distance formula to find the distance:

$$d = 10^{(m - M_V + 5)/5}$$

If you substitute the given apparent magnitude and absolute magnitude in the formula, you can determine that the distance is equal to $10^{3.7}$ pc, which equals about 5000 pc. This is one of the most common calculations in astronomy.

Once Shapley had calibrated the period–luminosity relation, he could use it to find the distance to any cluster in which he could identify those types of variable stars. By taking a series of photographic plates over a number of nights, Shapley was able to pick out the variable stars in a cluster, measure their average apparent magnitude, and find their periods of pulsation. Because the periods were very short, he knew the variable stars he saw in the clusters were the lowest-luminosity variable stars (now called RR Lyrae variables). Knowing that, he could read their absolute magnitude off the period–luminosity diagram. With the apparent magnitude and the absolute magnitude, he could calculate the distance to the star cluster.

This worked well for the nearer globular clusters, but variable stars in more distant clusters were too faint for him to detect. Shapley estimated the distances to these more distant clusters by calibrating the diameters of the clusters. For the



■ **Figure 15-4**

(a) Shapley's study of globular clusters showed that they were not centered on the sun, at the origin of this graph, but rather formed a great cloud centered far away in the direction of Sagittarius. Distances on this graph are given in thousands of parsecs, corresponding to Shapley's original calibration that produced values more than 2 times larger than the modern calibration. (b) Looking toward Sagittarius at visual wavelengths, you see nothing to suggest that this is the center of the galaxy. Interstellar dust and gas block your view. Only the distribution of globular clusters told Shapley the sun lay far from the center of the star system. (Daniel Good)

clusters whose distance he knew, he could use their angular diameters and the small-angle formula (see Chapter 3) to calculate linear diameters in parsecs. He found that the nearby clusters are about 25 pc in diameter, which he assumed is the average diameter of all globular clusters. He then used the angular diameters of the more distant clusters to find their distances. This is another illustration of calibration in astronomy.

Shapley later wrote that it was late at night when he finally plotted the directions and distances to the globular clusters on graph paper and found that, just as he had supposed, they formed a great swarm whose center lay many thousands of light-years in the direction of Sagittarius, confirming his suspicion that the center of the star system was not near the sun but was far away in Sagittarius (■ Figure 15-4). He found the only other person in the building, a cleaning lady, and the two stood looking at his graph

as he explained that they were the only two people on Earth who understood that humanity lives, not near the center of a small star system, but in the suburbs of a vast wheel of stars.

How did Shapley avoid the problem of obscuration by interstellar dust that limited earlier work by Kapteyn, the Herschels, and other astronomers? Shapley was able to see the globular clusters at great distances because they lie outside the plane of the galaxy (Figure 15-4) and are not dimmed much by the interstellar medium.

After Shapley's work, astronomers more strongly suspected that some of the faint patches of light visible through telescopes were other star systems. Within a few years they found evidence that the faint patches of light were indeed other galaxies much like our own Milky Way Galaxy. Today the largest telescopes can detect an estimated 100 billion galaxies similar to our own. Our home galaxy is special only in that it is our home.

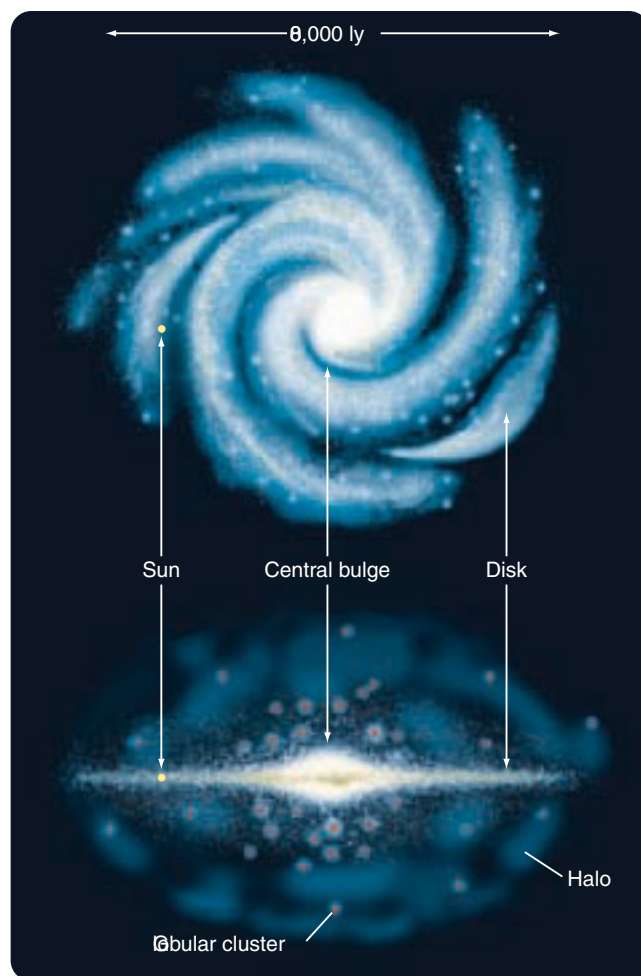
Shapley's study of star clusters led to the discovery that we live in a galaxy and that the universe is filled with similar galaxies. Like Copernicus, Shapley moved us from the center to the outskirts. A careful analysis of the structure of the galaxy will tell you the details about our real location.

15-2 Structure of the Galaxy

ASTRONOMERS COMMONLY GIVE the diameter of our galaxy as approximately 25 kpc, or 80,000 ly, and place the sun about two-thirds of the way from the center to the edge (■ Figure 15-5). Note that this is only the diameter of the easily detected part of our galaxy. Later in this chapter you will learn that the entire galaxy, some parts of which are not easy to observe, is much larger than 25 kpc in diameter.

The disk of the galaxy is often referred to as the **disk component**. It contains most of the galaxy's stars and nearly all of its gas and dust. Because the disk is home to the giant molecular clouds within which stars form (see Chapter 11), nearly all star formation in our galaxy takes place in the disk. Most of the stars in the disk are middle- to lower-main-sequence stars like the sun, a few are red giants and white dwarfs, and fewer still are brilliant blue O and B stars. Although those hot, massive stars are rare, they are so luminous that they provide much of the light from the disk.

Although astronomers can survey the locations and distances of the stars, they cannot cite a single number for the thickness of the disk because it lacks sharp boundaries. Also, the thickness of the disk depends on the kind of object studied. Stars like the sun, with ages of a few billion years, lie within about 500 pc above and below the central plane. In comparison, the youngest stars, including the O and B stars and the gas and dust from which these young stars form, are confined to a thin disk extending only about 50 pc above and below the plane (■ Figure 15-6). In proportion to its diameter



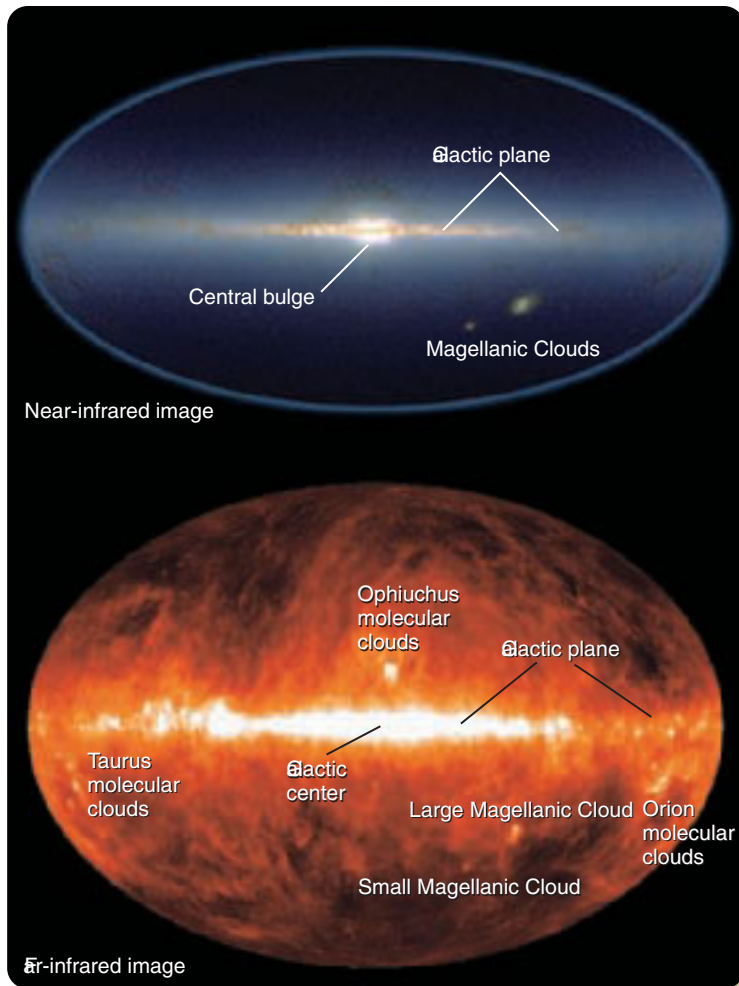
■ Figure 15-5

An artist's conception of our Milky Way Galaxy, seen face-on and edge-on. Note the position of the sun and the distribution of globular clusters in the halo. Hot blue stars light up the spiral arms. Only the inner halo is shown here. At this scale, the entire halo would be larger than a dinner plate. (©2003, 2004 Three Rivers Foundation)

of about 25 kpc, the disk of the galaxy is thinner than a thin pizza crust.

The disk of the galaxy contains both stellar associations and open star clusters. Associations are groups of 10 to a few hundred stars so widely scattered in space that their mutual gravity cannot hold them permanently together. From the turnoff points in their H-R diagrams (see Chapter 12), you can tell that they are very young groups of stars. The stars move together through space (■ Figure 15-7) because they formed from a single interstellar cloud and haven't had time to wander apart yet since they formed.

The second kind of cluster in the disk is the open cluster (see Figure 15-3), a group of 100 to a few thousand stars in a region about 25 pc in diameter. Because they have more stars in less space than associations, open clusters are more firmly

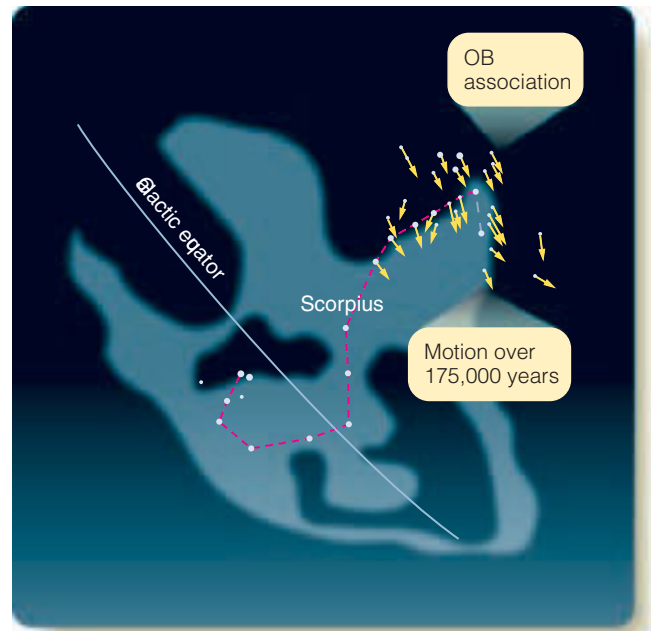


■ **Figure 15-6**

In these infrared images, the entire sky has been projected onto ovals with the center of the galaxy at the center. The central plane of the Milky Way extends from left to right. At near-infrared wavelengths, the central bulge is prominent, and dust clouds block your view. At longer wavelengths, the dust emits blackbody radiation and glows brightly. (Near-IR: 2MASS; Far-IR: DIRBE image courtesy Henry Freudenreich)

bound by gravity. Although they lose stars occasionally, they can survive for a long time, and the turnoff points in their H–R diagrams give ages from a few million to a few billion years.

If you look “up” or “down,” out of the galaxy’s disk, you are looking away from the dust and gas, so you can see into the galaxy’s **halo**, a spherical cloud of stars and star clusters that contains almost no gas and dust. Because the halo contains no dense gas clouds, it cannot make new stars. Halo stars are old, cool, lower-main-sequence stars; red giants; and white dwarfs. It is difficult to judge the extent of the halo, but it could have as much as 10 times the diameter of the visible disk.



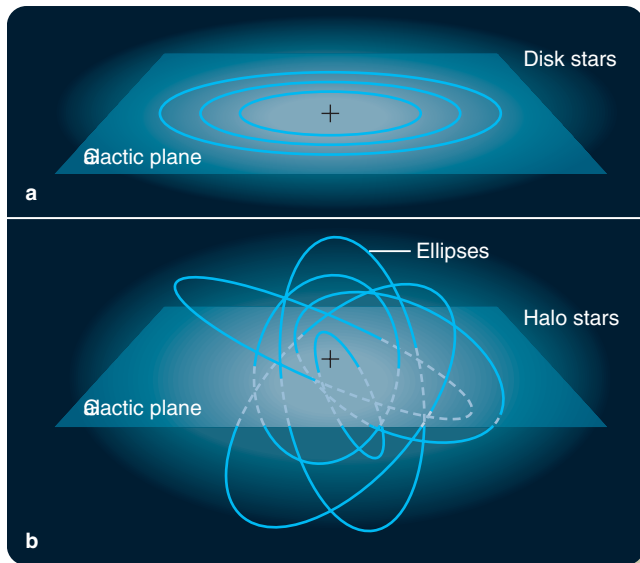
■ **Figure 15-7**

Many of the stars in the constellation Scorpius are members of an OB association that evidently formed recently from a single cloud of gas. As the stars orbit the center of our galaxy, they are moving together southwest along the Milky Way.

Around the center of our galaxy lies the **central bulge**, a flattened cloud of billions of stars about 6 kpc in diameter (see Figure 15-5). Like the halo, it contains little gas and dust. Astronomers often refer to the halo and the central bulge together as the **spherical component** of the galaxy. The central bulge is the most crowded part of the spherical component. Visible above and below the plane of the galaxy and through gaps in the obscuring dust, the central bulge contains mostly stars that are old and cool like the stars in the halo.

The halo includes roughly 200 globular clusters, each of which contains 50,000 to a million stars in a sphere a few tens of parsecs in diameter (refer again to Figure 15-3). Because they contain so many stars in such a small region, the clusters hold together very well gravitationally and have survived for billions of years. From the turnoff points in their H–R diagrams, you can tell their average age is about 11 billion years.

Orbital motions are quite different in the two components of the galaxy. Disk stars follow nearly circular orbits that lie in the plane of the galaxy (■ Figure 15-8a). Halo stars and globular clusters, however, follow highly elongated orbits tipped steeply to the plane of the disk (Figure 15-8b). Although the diagram shows these orbits as elliptical, the gravitational influence of the thick bulge forces them into curves that haven’t had time to wander apart yet. The dramatic difference between the motions of halo stars and disk stars will be important evidence when you consider the formation of the galaxy later in this chapter.



■ **Figure 15-8**

(a) Stars in the galactic disk have nearly circular orbits that lie in the plane of the galaxy. (b) Stars in the halo have randomly oriented, highly eccentric, elongated orbits.

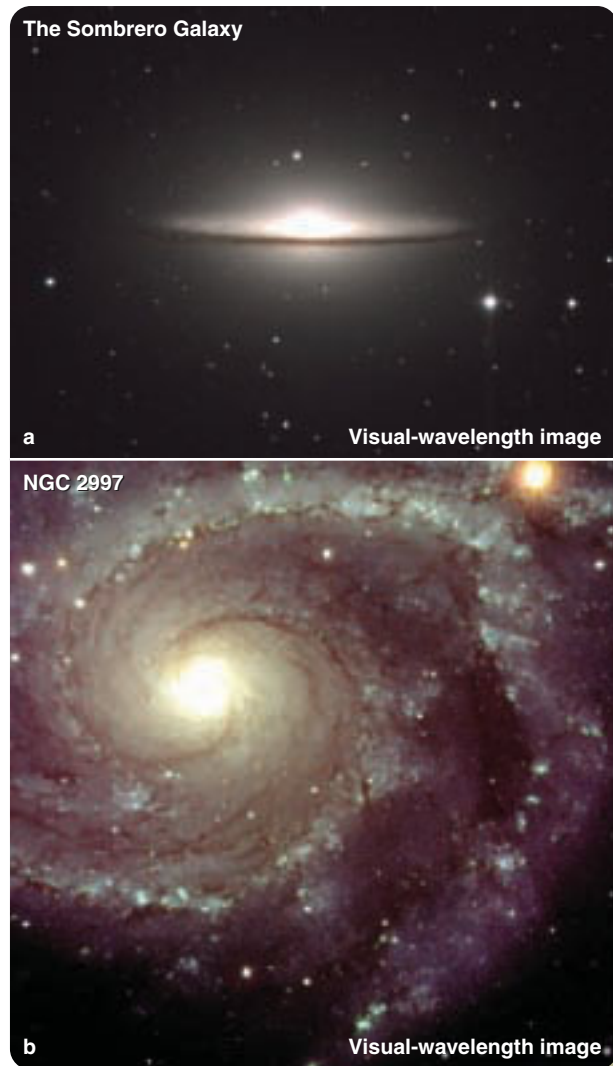
From the shape and size of our galaxy, astronomers conclude that we live in a spiral galaxy (■ Figure 15-9). The most impressive features of these disk galaxies are the spiral arms—long spiral patterns of bright stars, HII regions, star clusters, and clouds of gas and dust. The sun is located near the inside edge of one of these spiral arms. You will see later in this chapter how astronomers can observe the spiral arms in our own galaxy.

This analysis of the components of our galaxy may leave you wondering about one critical question: How much matter does our galaxy contain? To answer that question, you can measure our galaxy’s rotation.

The Mass of the Galaxy

To find the mass of an object, astronomers must observe the motion of another object orbiting it, just as in a binary star system. Humans don’t live long enough to see stars move significantly along their orbits around the galaxy, but astronomers can observe the radial velocities, proper motions, and distances of stars and then calculate the sizes and periods of their orbits. The results can reveal the mass of the galaxy.

Stars in the disk of the galaxy follow nearly circular orbits that lie in the plane of the disk (look again at Figure 15-8a). By observing the radial velocities of stars and other objects in various directions, astronomers conclude that the sun orbits the center of our galaxy at about 220 km/s, moving in the direction of Cygnus. The evidence suggests the sun’s orbit is nearly circular, so given the distance to the center of our galaxy, 8.0 kpc, you can find the circumference of the sun’s orbit by multiplying by 2π . If you divide the circumference of its orbit by its orbital velocity, you will discover that the sun has an orbital period of about 220 million years.



■ **Figure 15-9**

Our galaxy resembles the spiral galaxies visible through large telescopes. (a) Seen edge-on, spiral galaxies have central bulges and dust-filled disks. (Todd Boroson/NOAO/AURA/NSF) (b) Seen face-on, the spiral arms are dramatically outlined by hot O and B stars, emission nebulae, and dust. (ESO)

When you studied binary stars in Chapter 9, you saw that the total mass (in solar masses) of a binary star system equals the cube of the separation of the stars a (in AU) divided by the square of the period P (in years):

$$M = \frac{a^3}{P^2}$$

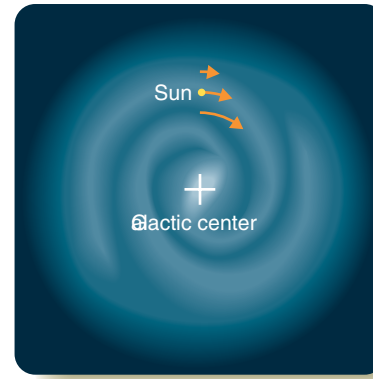
You can use the same equation here to find the mass of the galaxy. The radius of the sun’s orbit around the galaxy is about 8000 pc, and each parsec contains 2.06×10^5 AU. Multiplying, you find that the radius of the sun’s orbit is 1.65×10^9 AU. The orbital period is 220 million years, so the mass is:

$$M = \frac{(1.65 \times 10^9)^3}{(220 \times 10^6)^2} = 0.93 \times 10^{11} M_{\odot}$$

This is only a rough estimate because it does not include any mass lying outside the orbit of the sun. Allowing for that overlooked mass yields a lower limit to the total mass for our galaxy of at least 4×10^{11} (four hundred billion) solar masses.

The rotation of our galaxy is actually the orbital motion of each of its stars around the center of mass. Stars at different distances from the center revolve around the center of the galaxy with different periods, so stars starting near each other will draw apart as time passes (■ Figure 15-10), a situation called differential rotation. (Recall that differential rotation was first defined regarding the sun in Chapter 8.)

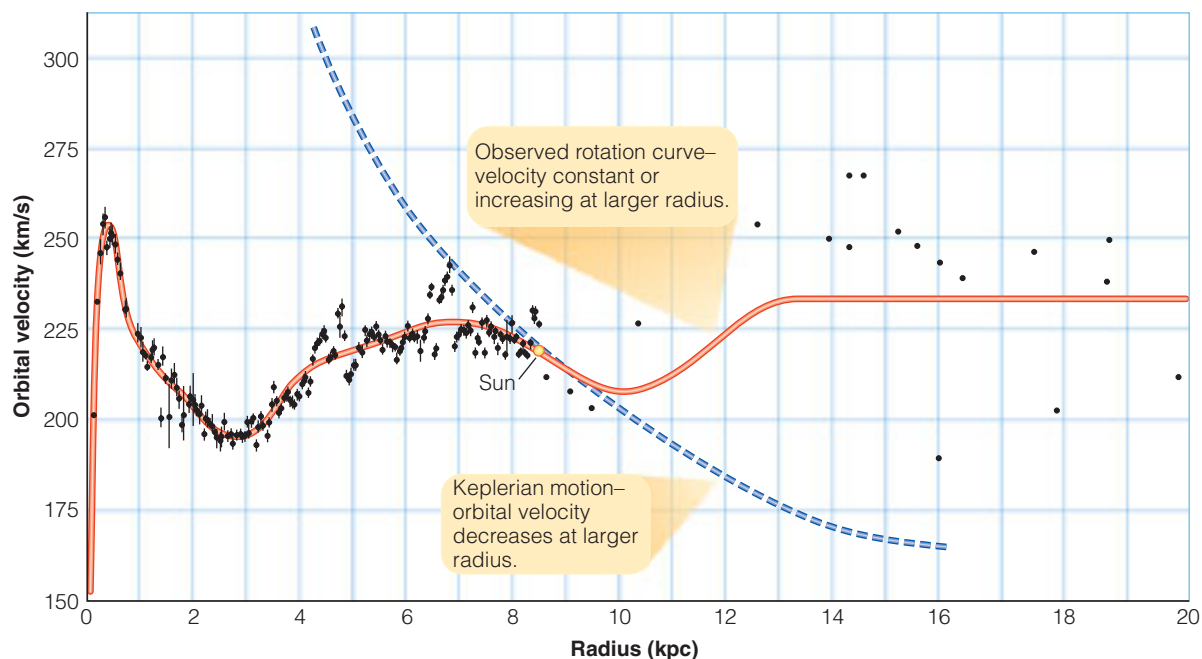
To fully describe the rotation of our galaxy, astronomers graph orbital velocity versus radius to produce a **rotation curve** (■ Figure 15-11). If all of the mass of the galaxy were concentrated near its center, you would expect to see orbital velocities decrease as you move away from the center. That is what you see in our solar system, where nearly all of the mass is concentrated in the sun. For that reason this is called **Keplerian motion**, referring to Kepler's laws. In contrast, the best observations of the rotation curve of the Milky Way show that orbital velocities in the outer disk are constant or even increasing with distance from the center of the galaxy. Those high orbital velocities indicate that the larger orbits enclose more mass and imply that our galaxy has much more mass than is contained within the radius of the sun's orbit.



■ **Figure 15-10**

The differential rotation of the galaxy means that stars at different distances from the center have different orbital periods. In this example, the star just inside the sun's orbit has a shorter period and pulls ahead of the sun, while the star outside falls behind.

Both observational evidence and mathematical models show that the extra mass lies in an extended halo sometimes called a **galactic corona** that may extend up to 10 times farther than the edge of the visible disk and could contain more than a trillion (10^{12}) solar masses. Most of that mass is invisible, neither emitting nor absorbing light, so astronomers refer to it as **dark matter**. Some of the mass in the galactic corona is made up of low-luminosity stars and white dwarfs, but much of the mass must be some other form of matter. You will learn more about the problem of dark matter in the following two chapters. The nature of dark matter is one of the fundamental unknowns in modern astronomy.



■ **Figure 15-11**

The rotation curve of our galaxy is plotted here as orbital velocity versus radius. Data points show measurements made by radio telescopes. Observations outside the orbit of the sun are much more uncertain, and the data points scatter widely. Orbital velocities do not decline outside the orbit of the sun, as you would expect if most of the mass of the galaxy were concentrated toward the center (Keplerian motion). Rather, the curve is approximately flat at great distances, suggesting that the galaxy contains significant mass outside the orbit of the sun. (Adapted from a diagram by Françoise Combes)

SCIENTIFIC ARGUMENT

If dust and gas block the view, how do astronomers know how big our galaxy is?

Because scientific arguments depend ultimately on evidence, they must explain how scientists know what they know. Interstellar dust in our galaxy blocks the view only in the plane of the galaxy. When you use a telescope to look away from the plane of the galaxy, you are looking out of the obscuring interstellar medium and can see to great distances. The globular clusters are scattered through the halo, with a strong concentration in the direction of Sagittarius. When astronomers look above or below the plane of the galaxy, they can see those clusters, and careful observations reveal variable stars in the clusters. They can then find the distances to those clusters by using modern calibrations of the Cepheid and RR Lyrae variable stars' period–luminosity diagrams. Astronomers infer that the distance to the center of the distribution of globular clusters is the distance to the center of the galaxy because they assume that the distribution of clusters is controlled by the gravitation of the galaxy as a whole.

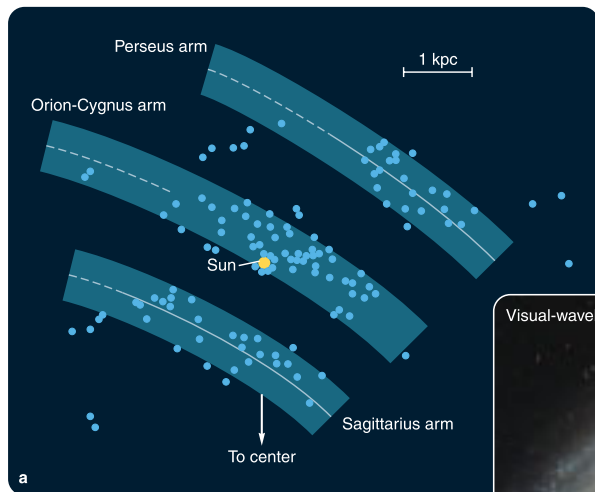
In any logical argument, it is important to ask “How do we know?” and that is especially true in science. Create a new argument: **What measurements and assumptions reveal the total mass of our galaxy?**

15-3 Spiral Arms and Star Formation

THE MOST STRIKING FEATURE of galaxies like the Milky Way is their patterns of spiral arms that wind outward through the disk. These arms contain swarms of hot, blue stars; clouds of dust and gas; and young star clusters. The young objects suggest that the spiral arms involve star formation, but, as you try to understand the spiral arms, you need to consider two problems. First, how can anyone be sure our galaxy has spiral arms if interstellar dust obstructs our view? Second, why doesn't the differential rotation of the galaxy destroy the arms? The solution to both problems involves star formation.

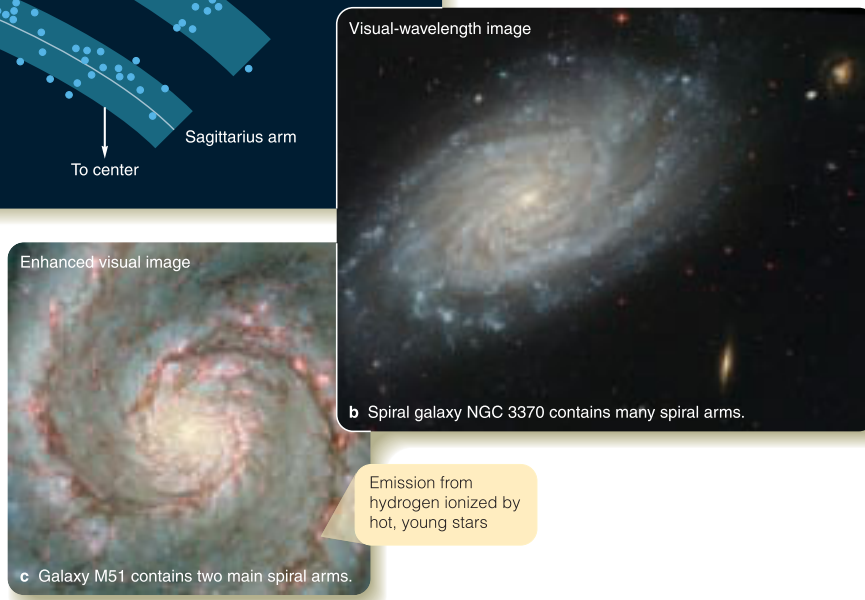
Tracing the Spiral Arms

As you have already learned, O and B stars are often found in associations and are very luminous. Thus, they are easy to detect across great distances. Unfortunately, at those great distances their parallax is too small to measure, so their distances must be found by other means, usually by spectroscopic parallax (see Chapter 9). Astronomers find that OB associations are not located randomly but lie along segments of three spiral arms near the sun (■ Figure 15-12). Those arms have been named for the



■ **Figure 15-12**

(a) Nearby young O and B stars in our galaxy fall along bands that appear to be segments of spiral arms. (b) Many of the galaxies in the sky are disk shaped like our galaxy, and most of those galaxies have spiral arms. (c) Images of other galaxies show that spiral arms are marked especially by hot luminous stars and emission nebulae that must be very young. This should make you suspect that spiral arms are related to star formation. (Images: NASA, Hubble Heritage Team)



prominent constellations through which they pass. Astronomers can use infrared and radio telescopes to penetrate the interstellar dust and gas, locate more distant OB associations, and trace the spiral arms even farther.

Objects used to map spiral arms are called **spiral tracers**. Aside from OB associations, spiral tracers include young open star clusters, clouds of hydrogen ionized by hot stars (emission nebulae), and certain higher-mass variable stars. Notice that all spiral tracers are young objects, formed recently, astronomically speaking. O stars, for example, live for only a few million years. If their orbital velocity is about 200 km/s, they cannot move more than about 500 pc in their lifetimes. This is less than the width of a spiral arm. Because they don't live long enough to move away from the spiral arms, they must have formed there.

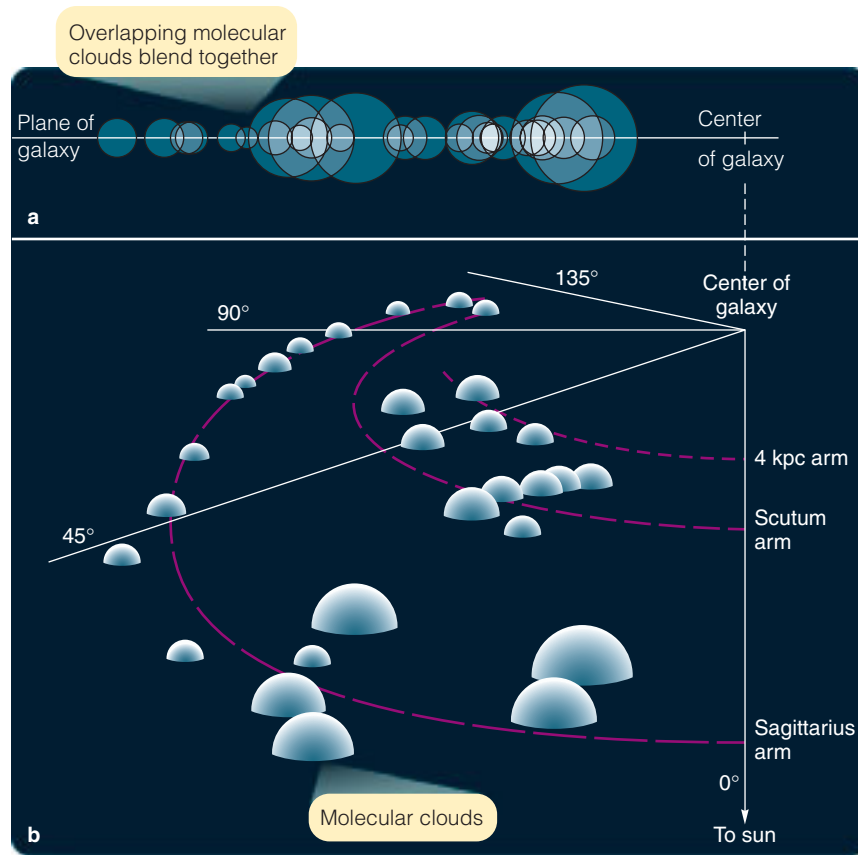
Studies of other galaxies show that their spiral arms are also marked by hot blue stars and other spiral tracers, as in our galaxy (Figure 15-12c). The youth of spiral tracers is an important clue about spiral arms. Obviously spiral arms are associated with star formation. Before you can follow this clue, you need to extend your map of spiral arms to show the entire galaxy.

Radio Maps of Spiral Arms

The dust that blocks the view at visual wavelengths is transparent to radio waves because radio wavelengths are much larger than the diameter of the dust particles. If you point a radio telescope at a section of the Milky Way, you will receive signals from gas clouds along your line of sight in spiral arms at various distances across the galaxy. Signals from different clouds can be separated by measuring the Doppler shifts of the spectral lines.

Radio astronomers use the strong spectral line emission from carbon monoxide (CO) to map the location of giant molecular clouds in the plane of the galaxy. Recall from Chapter 11 that those clouds are sites of active star formation. Maps constructed from such observations reveal that the giant molecular clouds are located along the spiral arms (■ Figure 15-13).

Observing at a wavelength of 21 cm allows detection of atomic hydrogen (see Figures 10-6 and 10-7), warmer than the material in molecular clouds (■ Figure 15-14). Just as for the molecular clouds, analysis of the radial velocity data requires that astronomers start with estimates of the orbital velocities at different distances from the center of the galaxy. Because those velocities are not precisely known and because turbulent motions in the gas distort the radial velocities, the atomic hydrogen map doesn't trace a perfect spiral pattern. In the direction toward the center of the galaxy there is an additional problem. There, the orbital motions of gas clouds are perpendicular to the line of



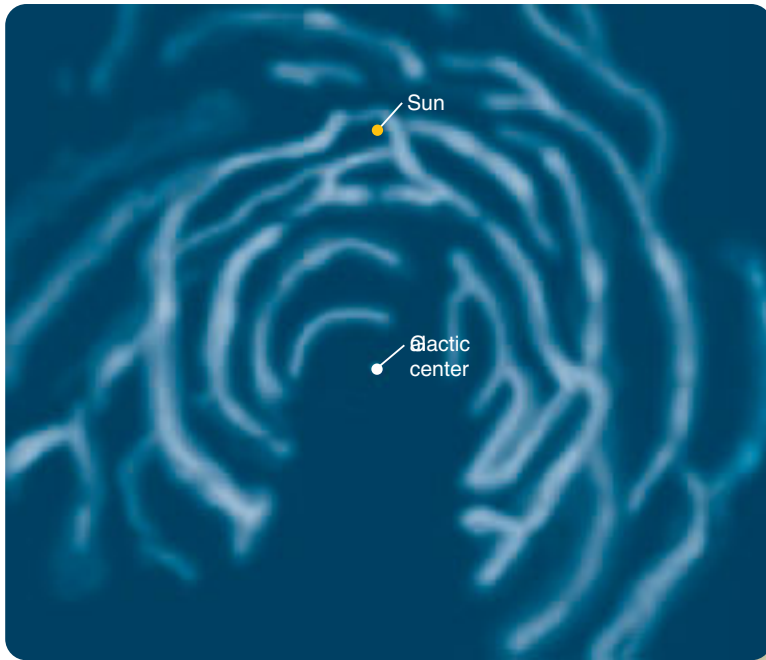
■ **Figure 15-13**

(a) At the wavelength emitted by the CO molecule, astronomers find many molecular clouds along the Milky Way, but the clouds overlap in a confusing jumble. By using a model of the rotation of the galaxy and the radial velocities of the clouds, radio astronomers can estimate the distances to each cloud and use them to map spiral arms. (b) This map represents the view from a point 2 kpc directly above the sun. The molecular clouds, shown here as hemispheres extending above the plane of our galaxy, are located along spiral arms. Angle labels indicate galactic longitudes. (Adapted from a diagram by T. M. Dame, B. G. Elmegreen, R. S. Cohen, and P. Thaddeus)

sight, and all of the radial velocities are zero. That is why the map in Figure 15-14 is empty in the wedge-shaped region directly toward the center.

Radio maps combined with studies at infrared and visible wavelengths can be used to paint a picture of our galaxy viewed from the inside. Clearly we live in a spiral galaxy, but the spiral pattern appears to be slightly irregular, with many branches and gaps. The stars you see in Orion, for example, appear to be in a detached segment of a spiral arm, referred to as a “spur.”

In addition to helping map the arrangement of spiral arms, infrared observations indicate that the central bulge of our galaxy is not a sphere but rather an elongated bar pointing partially away from Earth. The spiral arms may stem from a ring that encloses this bar. In the next chapter, you will see that such

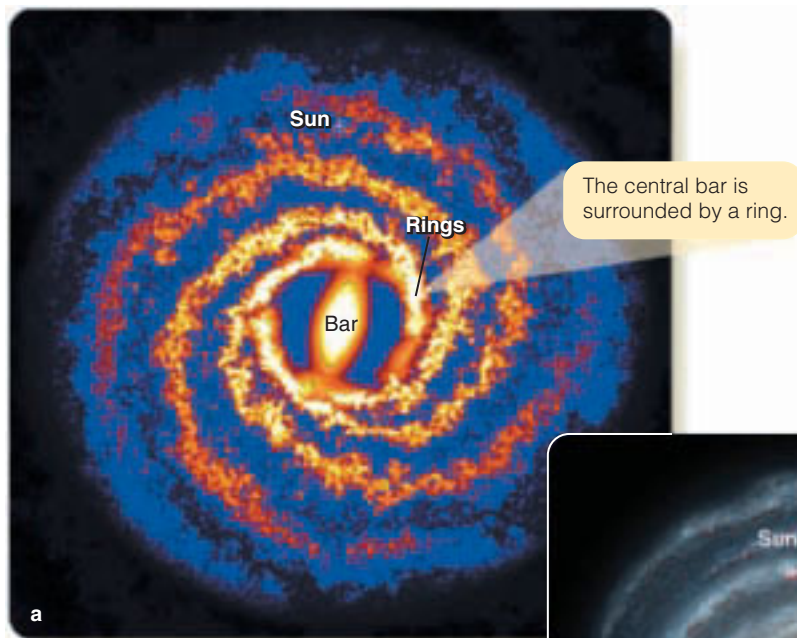


■ **Figure 15-14**

This 21-cm radio map of our galaxy confirms that concentrations of neutral hydrogen gas lie approximately in a spiral, but the pattern is complex and suggests branches and spurs. (Adapted from a radio map by Gart Westerhout)

structures are common in other galaxies. By combining observations of our own galaxy with studies of other galaxies, astronomers can construct a best guess at what the Milky Way Galaxy might look like viewed from outside (■ Figure 15-15).

One important fact revealed by the radio maps is that spiral arms are regions of higher gas density. Spiral tracers tell you that the arms contain young objects, so you suspect they must also have active star formation. Radio maps confirm your suspicion by telling you that the material needed to make stars is abundant and concentrated in spiral arms.



■ **Figure 15-15**

(a) This model of our galaxy is based on far-infrared observations of dust and includes four spiral arms with no branches springing from a ring around a central bar. (Courtesy Henry Freudenreich) (b) This artist's impression of a two-armed model is based on observations with the Spitzer infrared space telescope. Notice the larger central bar. (NASA/JPL-Caltech/R. Hurt, SSC)



The Spiral Density Wave Theory

Just what are spiral arms? You can be sure they are not physically connected structures like bands of magnetic field that hold the gas in place. If they were, the differential rotation of the galaxy would destroy them within just a few hundred million years, winding them up and tearing them apart like paper streamers caught on the wheel of a speeding car. Yet spiral arms are common in galaxies (■ Figure 15-16), so they must last for billions of years.

Astronomers conclude that spiral arms are dynamically stable—they retain the same appearance even though the gas, dust, and stars in them are constantly changing. To see how this works, think of the traffic jam behind a slow-moving truck. Seen from an airplane, the traffic jam would be stable, moving slowly down the highway. But you could watch an individual car approach from behind, slow down, wait its turn, finally reach the front of the jam, pass the truck, and resume speed. The individual cars in the jam are constantly changing, but the traffic jam itself is a dynamically stable shape, moving at its own speed along the highway.

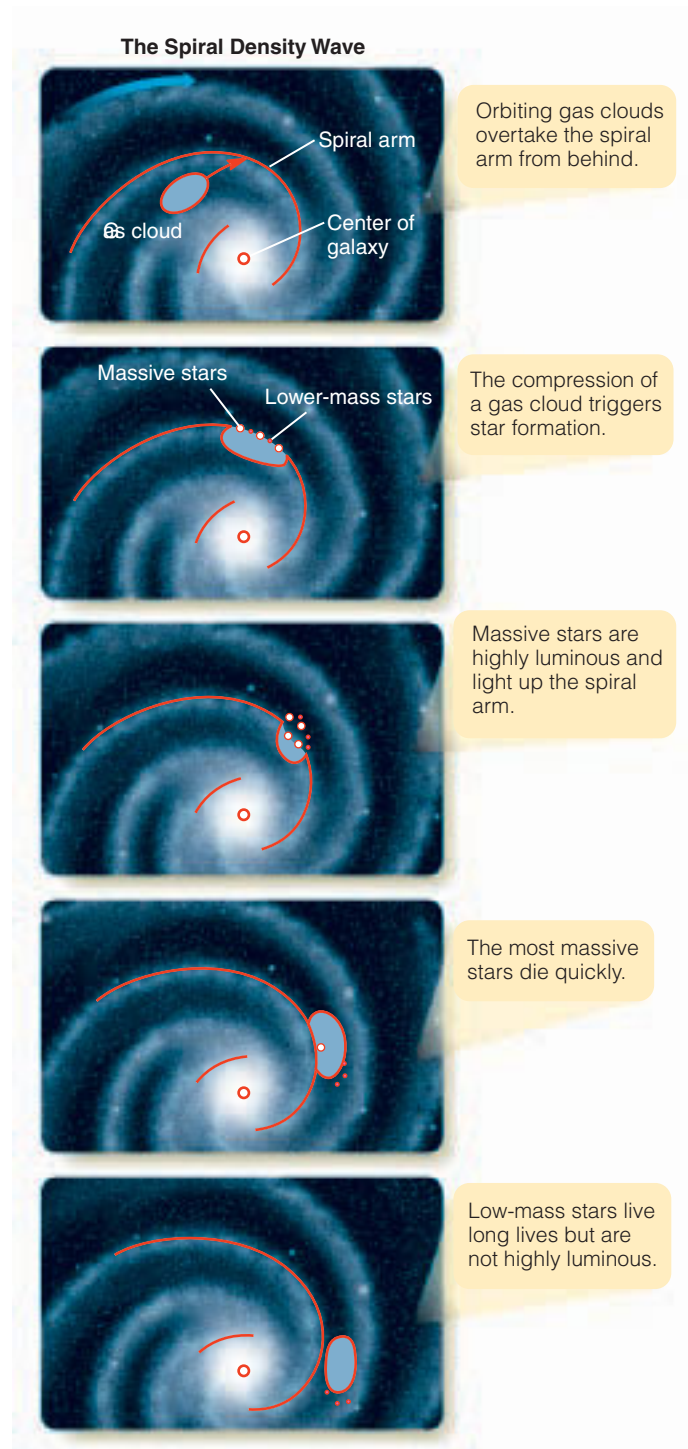
In the **density wave theory**, the galaxy's spiral arms are dynamically stable regions of compression that move slowly around the galaxy, just as the truck moves slowly down the highway. Gas clouds moving at orbital velocity around the galaxy overtake the slow-moving arms from behind and slam into the gas already in the arms. The sudden compression of the gas can



■ **Figure 15-16**

Typical of spiral galaxies, M83 has a two-armed spiral pattern with prominent dust lanes and bright O and B stars along the arms. This galaxy's spiral also contains branches and spurs. (European Southern Observatory)

trigger the collapse of the gas clouds and the formation of new stars (see Chapter 11). Newly formed stars and the remaining gas eventually move on through the arm and emerge from the front of the slow-moving arm to resume their travels around the galaxy (■ Figure 15-17).



■ **Figure 15-17**

According to the spiral density wave theory, star formation occurs as gas clouds pass through spiral arms.

Science depends on evidence, so you should ask what evidence astronomers have that spiral arms are caused by spiral density waves. Spiral tracers are the key. Stars of all masses are forming in spiral arms, but the O and B stars live such short lifetimes that they die before they can move out of the spiral arm. These massive, high-luminosity stars, along with gas and dust, confirm that spiral arms are sites of star formation. Lower-mass stars, such as the sun, can't be used as spiral tracers. They also form in spiral arms, but, because they live so long, they leave the arms in which they were born and circle the galaxy many times. The sun probably formed as part of an association in a star-forming region within a spiral arm almost 5 billion years ago, escaped from that association, and has circled the galaxy about 20 times, passing through spiral arms many times. Therefore, plotting the locations of sunlike stars does not reveal the spiral pattern because such stars live too long.

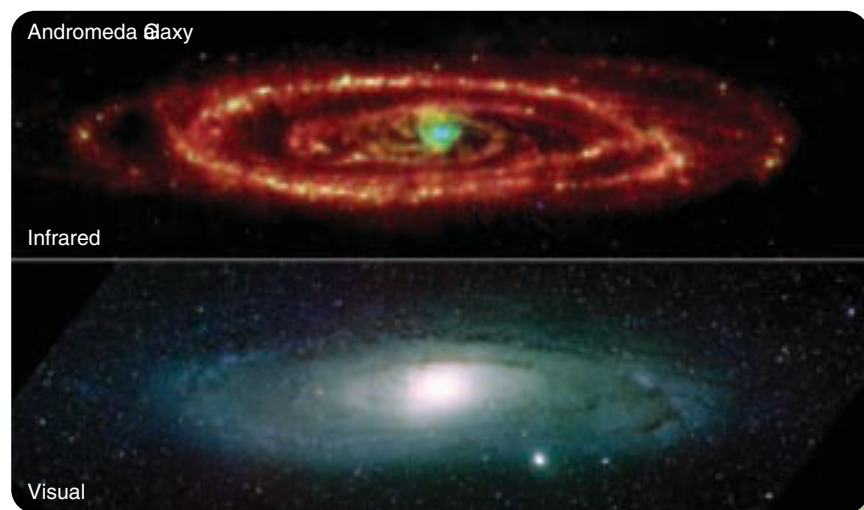
Giant molecular clouds and thick dust in the arms (■ Figure 15-18) are evidence that material is compressed in the arms and fostering active star formation. These clouds can convert up to 30 percent of their mass into stars. The Orion complex and the Ophiuchus dark cloud are examples of regions filled with infrared protostars (see Chapter 11). Such a cloud can form stars for 10 to 100 million years before it is disrupted by radiation pressure and winds from the most massive new stars. At their normal speeds, clouds need about that long to pass through a spiral arm.

The evidence seems to fit the spiral density wave theory well, but the theory has two problems. First, how does the

complicated spiral disturbance begin, and how is it sustained? Computer models indicate that spiral density waves should slowly die out in about a billion years, so something must regenerate the spiral wave. Other models show that the disk of the galaxy is naturally unstable to (affected by) certain types of disturbances, just as a guitar string is unstable to certain vibrations. Any sudden jostling—the rumble of a passing truck, for example—can set the string vibrating at its natural frequencies. Similarly, minor fluctuations in the galaxy's disk, such as supernova explosions, might be able to regenerate the spiral waves.

Another possibility is that large gravitational perturbations can generate a spiral density wave. As you learned earlier, observations show that the center of our galaxy is not a sphere but a bar. The rotation of that bar could continuously disturb the disk of the galaxy and stimulate the formation of a spiral density wave. A close encounter with a passing galaxy could also stimulate a spiral pattern.

The second problem for the density wave theory involves the spurs and branches observed in the arms of our own and other galaxies. Computer models of density waves produce regular, simple two-armed spiral patterns. Some galaxies, called **grand-design** galaxies, do indeed have symmetric two-armed patterns, but others do not (■ Figure 15-19). Some galaxies have a great many short spiral segments, giving them a fluffy appearance, but no overall grand design. These galaxies have been termed **flocculent**, meaning “woolly.” Our galaxy seems to be intermediate between the extremes of flocculent versus grand-design. How can astronomers explain these variations in the spiral pattern? Perhaps the answer lies in a process that sustains star formation once it begins.



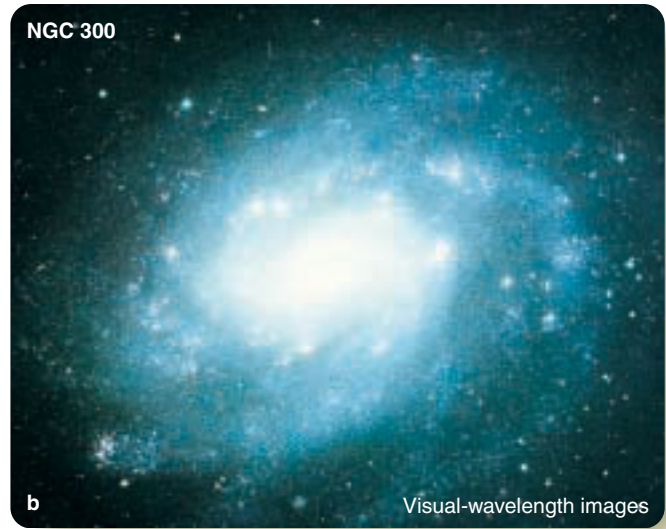
■ **Figure 15-18**

Besides bright stars, spiral arms also contain clouds of gas and dust. In the Andromeda Galaxy, dust clouds glow brightly in the infrared and outline the spiral arms. (NASA/JPL-Caltech/K. Gordon and NOAO/AURA/NSF)

Self-Sustaining Star Formation

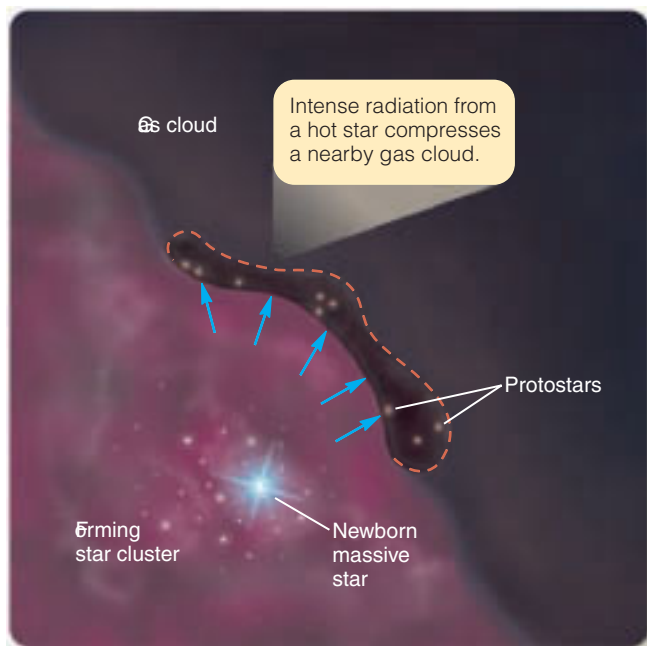
Star formation is a critical process in the creation of spiral arms. It not only makes spiral arms visible but may also shape the spiral pattern itself.

Star formation can control the shape of spiral patterns if the birth of stars in a cloud of gas is able to renew itself by triggering the formation of more new stars. Consider a newly formed star cluster with a single massive star. There are several ways in which this massive star can compress the surrounding gas to trigger more star formation: by sending out strong winds and bipolar jets as it forms, by the pressure of its intense radiation (■ Figure 15-20), or by the explosive expansion caused by its eventual death as a supernova. Examples of such **self-sustaining star formation** have been found. The Orion complex, consisting of the Great



■ **Figure 15-19**

(a) Some galaxies are dominated by two spiral arms; but, even in these galaxies, minor spurs and branches are common. Spiral density waves can generate the two-armed, grand-design pattern, but self-sustained star formation may be responsible for the irregularities. (b) Many spiral galaxies do not appear to have two dominant spiral arms. Spurs and branches suggest that star formation is proceeding rapidly in such galaxies. (Anglo-Australian Telescope Board)



■ **Figure 15-20**

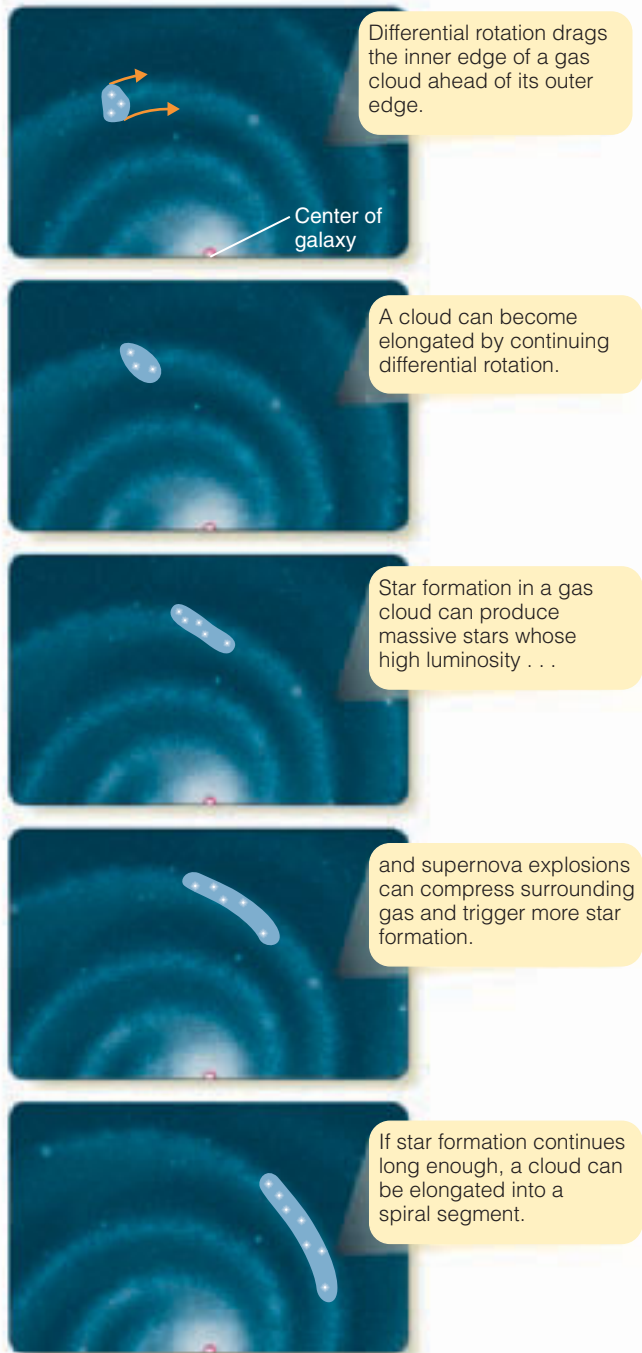
Most stars in a star cluster are too small and too cool to affect nearby gas clouds; but, once a massive star forms, it becomes so hot and so luminous its radiation can push gas away and compress a nearby gas cloud. In the densest regions of the compressed cloud, new stars can begin forming.

Nebula in Orion and the star formation buried deep in the dark interstellar clouds behind the nebula, is such a region (see Chapter 11).

Self-sustaining star formation can produce growing clumps of new stars, and the differential rotation of the galaxy can drag the inner edge ahead and let the outer edge lag behind to produce a cloud of star formation shaped like a segment of a spiral arm: a spur (■ Figure 15-21). Mathematical models of galaxies filled with such segments of spiral arms do have a spiral appearance but without the strong two-armed pattern of the grand-design spirals. Astronomers suspect that a spiral density wave can generate beautiful two-armed spiral patterns, but the self-sustaining star formation process produces the branches and spurs so prominent in flocculent galaxies.

The discussion of star formation in spiral arms illustrates the understanding of nature in terms of processes. The spiral density wave creates graceful arms, but it is the star formation in the arms that makes them stand out so prominently. Self-sustaining star formation can act in some galaxies to modify the spiral arms and produce branches and spurs. In some galaxies, it can make

Self-Sustaining Star Formation



■ **Figure 15-21**

Self-sustaining star formation may be able to produce long clouds of young stars that look like segments of spiral arms.

the spiral pattern flocculent. By searching out and understanding the details of such natural processes, astronomers can begin to understand the overall structure and evolution of the universe we live in.

SCIENTIFIC ARGUMENT

Why can't astronomers use solar-type stars as spiral tracers?

Sometimes the timing of events is the critical factor in a scientific argument. In this case, you need to think about the evolution of stars and their orbital periods around the galaxy. Stars like the sun live about 10 billion years, but the sun's orbital period around the galaxy is 220 million years. The sun almost certainly formed when a gas cloud passed through a spiral arm, but since then the sun has circled the galaxy many times and has passed through spiral arms often. That means the sun's present location, which happens coincidentally to be near a spiral arm, is not due to the location of that arm. An O star, however, lives only a few million years. It is born in a spiral arm and lives out its entire lifetime before it can leave the spiral arm. Short-lived stars such as O stars are found only in spiral arms, but G stars are found all around the galaxy.

The spiral arms of our galaxy would make it beautiful if it could be photographed from a distance, but we are trapped inside it. Create an argument based on evidence: **How do astronomers know that the spiral arms mapped out near us by spiral tracers actually extend across the disk of our galaxy?**

15-4 The Nucleus

THE MOST MYSTERIOUS REGION of our galaxy is its very center, the nucleus. At visual wavelengths, this region is totally hidden by dust that dims the light it emits by 30 magnitudes. If a trillion (10^{12}) photons of light left the center of the galaxy on a journey to Earth, only one of those photons would make it through the dust. Consequently, visual-wavelength images reveal nothing about the nucleus. Observations at infrared and radio wavelengths can see through the interstellar material, and those images show a region of tremendously crowded stars orbiting in the nucleus at high velocity. To understand what is happening in the innermost regions of our galaxy, you need to carefully compare observations and hypotheses.

Observations of the Galactic Nucleus

If you look up at the Milky Way on a dark night, you might notice a slight thickening in the direction of the constellation Sagittarius, but nothing specifically identifies this as the direction of the heart of the galaxy. Even Shapley's study of globular clusters identified the location only approximately. The first complete infrared map of the central bulge made by Eric Becklin in 1968 showed the location of intense radiation where the stars are most crowded together, the gravitational core of the galaxy. High-resolution radio maps of that stellar center revealed a complex collection of radio sources, with one, **Sagittarius A*** (abbreviated Sgr A* and usually pronounced "sadge A-star"), lying at the exact location of the galactic nucleus.

Observations show that Sgr A* is less than 1 AU in diameter but is a strong source of radio energy as well as X-ray emission

(short-wavelength X-rays can also penetrate interstellar dust and gas). The tremendous amount of infrared radiation coming from the central area appears to be produced by crowded stars and by dust warmed by those stars. But what could be as small as Sgr A* and produce so much radio and X-ray energy?

Read **Sagittarius A*** on pages 320–321 and notice three important points:

- 1 Observations at radio and infrared wavelengths reveal complex structures near Sgr A* caused by magnetic fields and by rapid star formation. Supernova remnants show that massive stars have formed there recently and exploded at the ends of their lives.
- 2 The center is crowded. Tremendous numbers of stars heat the dust, which emits strong infrared radiation.
- 3 Finally, there is evidence that Sgr A* is a supermassive black hole into which gas is flowing.

A supermassive black hole is an exciting idea, but scientists must always be aware of the difference between adequacy and necessity. A supermassive black hole is adequate to explain the observations, but is it necessary? Could there be other explanations? For example, some astronomers have suggested that gas flowing inward could trigger tremendous bursts of star formation. Such hypotheses have been considered and tested against the evidence, but none appears to be adequate to explain all the observations. So far, the only hypothesis that seems adequate is that our galaxy's nucleus is home to a supermassive black hole.

Meanwhile, observations are allowing astronomers to refine their models. For instance, Sgr A* is not as bright in X-rays as it should be if it has a hot accretion disk with matter constantly flowing into the black hole. Observations of X-ray and infrared flares lasting only a few hours suggest that mountain-size blobs of matter may occasionally fall into the black hole and be ripped apart and heated by tides. But the black hole seems to be mostly dormant, lacking a fully developed hot accretion disk because little matter is flowing into it at the present time.

Such a supermassive black hole could not be the remains of a single dead star. It contains too much mass. It probably formed when the galaxy first formed over 13 billion years ago. In later chapters you will see that such supermassive black holes are found at the centers of many galaxies.

SCIENTIFIC ARGUMENT

Why do astronomers think the center of our galaxy contains a large mass?

Because scientific arguments usually hinge on evidence, they often involve discussions of measurement—one of the keys to science. The best way to measure the mass of an astronomical object is to watch something orbit around it. Then, you can use Kepler's third law to find the mass inside the orbit. Because of gas and dust, astronomers can't see to the center of our galaxy at visual

wavelengths, but infrared observations can detect individual stars orbiting Sgr A*. The star S0-2 has been particularly well observed, but a number of stars can be followed as they orbit the center. The sizes and periods of these orbits, interpreted using Kepler's laws, reveal that Sgr A* contains roughly 4 million solar masses.

Now build a new argument to analyze a different observation. **The strong infrared radiation at wavelengths longer than 4 microns (4000 nm) implies vast numbers of stars crowded into the center. Why?**

15-5 Origin and History of the Galaxy

JUST AS DINOSAURS LEFT BEHIND fossilized footprints, our galaxy has left behind clues about its youth. The stars of the spherical component are old and must have formed long ago when the galaxy was very young.

Stellar Populations

In the 1940s, astronomers realized that there are two families of stars in the galaxy. They form and evolve in similar ways, but they differ in the abundances of atoms that are heavier than helium—atoms that astronomers call **metals**. (Note that this is not the way the word *metal* is defined by non-astronomers.) **Population I stars** are metal-rich, containing 2 to 3 percent metals, whereas **Population II stars** are metal-poor, containing only about 0.1 percent metals or less. The difference may seem small, but it is dramatically evident in spectra (■ Figure 15-22).

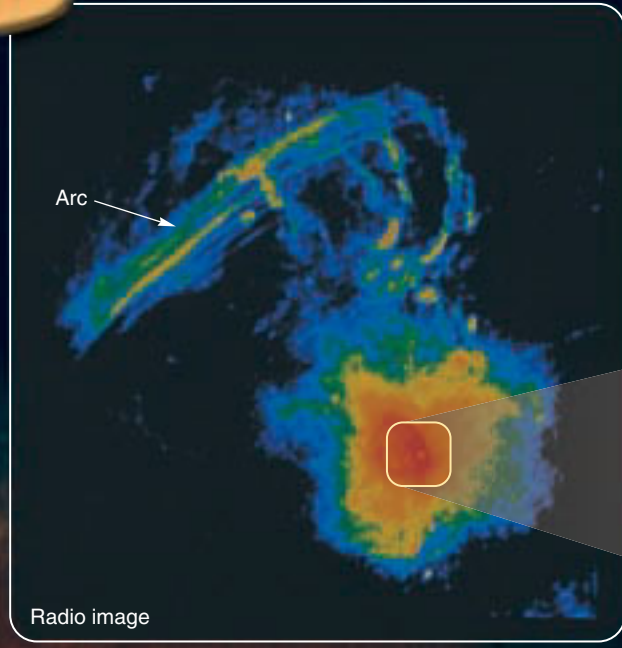
Population I stars belong to the disk component of the galaxy and are sometimes called disk population stars. They have nearly circular orbits in the plane of the galaxy and are relatively young stars that formed within the last few billion years. The sun is a Population I star, as are the type I Cepheid variables discussed in this chapter and in Chapter 12.

Population II stars belong to the spherical component of the galaxy and are sometimes called the halo population stars. These stars have randomly tipped orbits ranging from circular to highly elliptical. They are old stars that formed when the galaxy was young. The metal-poor globular clusters are part of the halo population, as are the RR Lyrae and type II Cepheids.

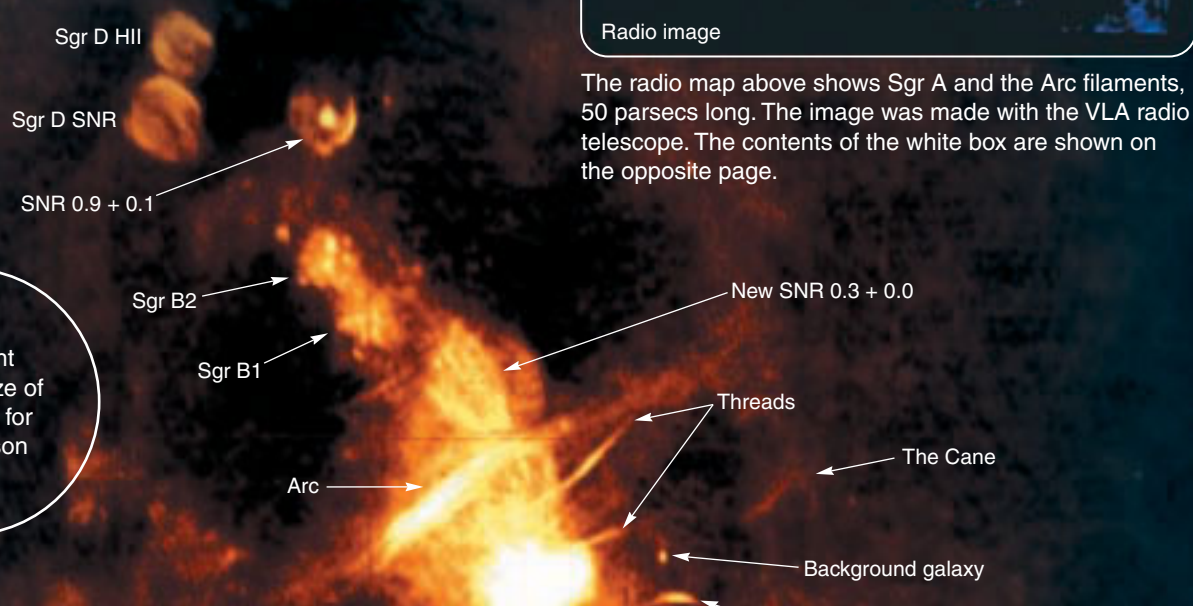
Since the discovery of stellar populations, astronomers have realized that there is a gradation between populations. Extreme Population I stars are found only in the spiral arms. Slightly less metal-rich Population I stars, called intermediate Population I stars, are located throughout the disk. The sun is an intermediate Population I star. Stars that are even less metal rich, such as stars in the central bulge, belong to the intermediate Population II. The most metal-poor stars are those in the halo, including those in globular clusters. Those are referred to as extreme Population II stars.

Sagittarius A*

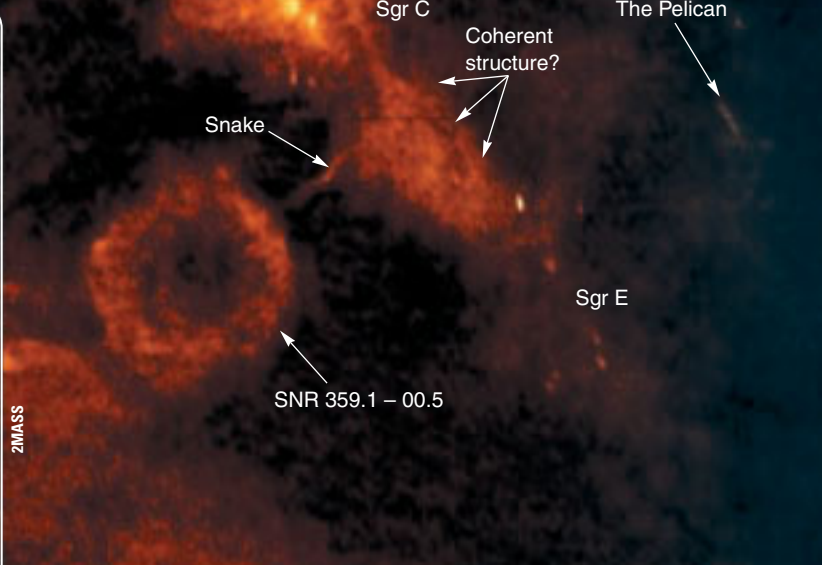
1 There is so much interstellar dust in the plane of the Milky Way that you cannot observe the nucleus of our galaxy at visual wavelengths. The image below is a radio image of the innermost 300 pc. Many of the features are supernova remnants (labeled SNR), and a few are star formation clouds. Peculiar features such as threads, the Arc, and the Snake may be gas trapped in magnetic fields. At the center of the image lies Sagittarius A, the location of the nucleus of our galaxy.



The radio map above shows Sgr A and the Arc filaments, 50 parsecs long. The image was made with the VLA radio telescope. The contents of the white box are shown on the opposite page.



2 Infrared photons with wavelengths longer than 4 microns (4000 nm) are emitted almost entirely by warm interstellar dust. The radiation at those wavelengths coming from Sagittarius is intense, indicating that this region contains lots of dust, and is crowded with stars that warm the dust.



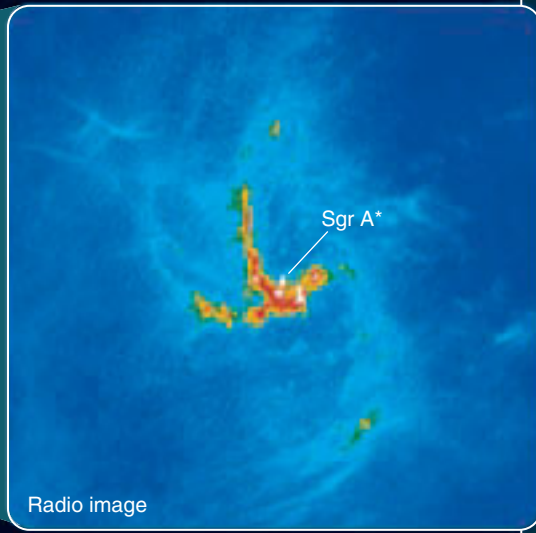
Infrared image

NRAO/AUI/NSF

NRL

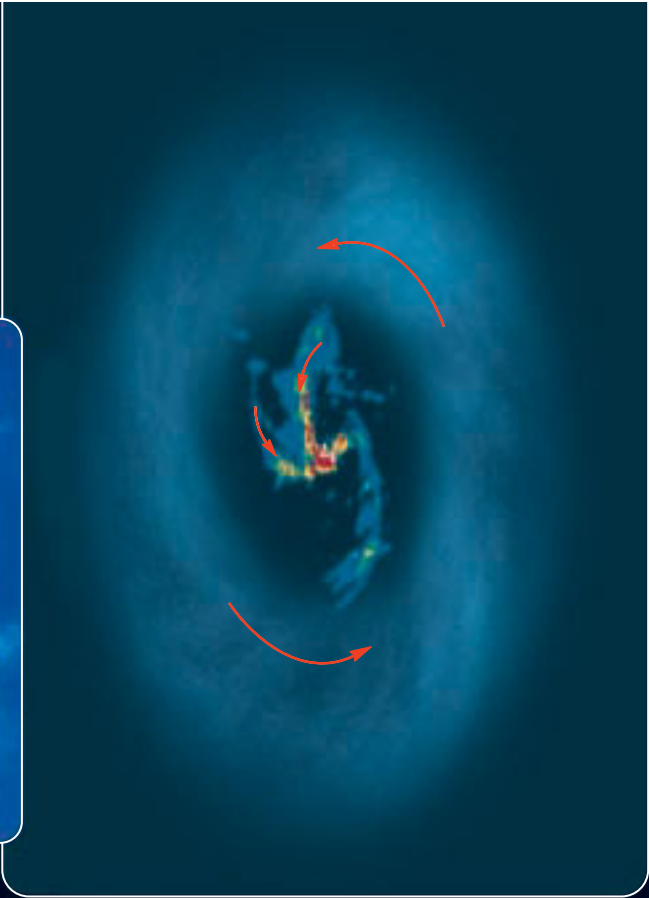
ZMASS

1a This high-resolution radio image of Sgr A (within the white box in the small-scale map on the opposite page) reveals a spiral swirl of gas around an intense radio source known as Sgr A*, about 3 pc across, this spiral lies in a low-density cavity inside a larger disk of neutral gas. The arms of the spiral are thought to be streams of matter flowing into Sgr A* from the inner edge of the larger disk (drawing at right).



Radio image

N. Killeen and Kwok-Yung Lo



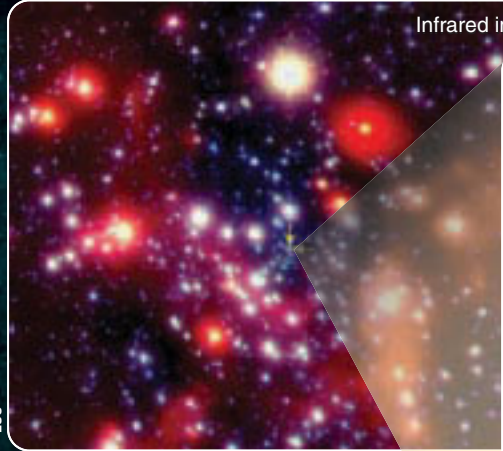
Evidence of a Black Hole in the Nucleus of Our Galaxy

3 Since the middle 1990s, astronomers have been able to use large infrared telescopes and active optics to follow the motions of stars orbiting around Sgr A*. A few of those orbits are shown here. The size and period of the orbit allows astronomers to calculate the mass of Sgr A* using Kepler's third law. The orbital period of the star SO-2, for example, is 15.2 years, and the semimajor axis of its orbit is 950 AU. The combined motions of the observed stars suggest that Sgr A* has a mass of 4 million solar masses.

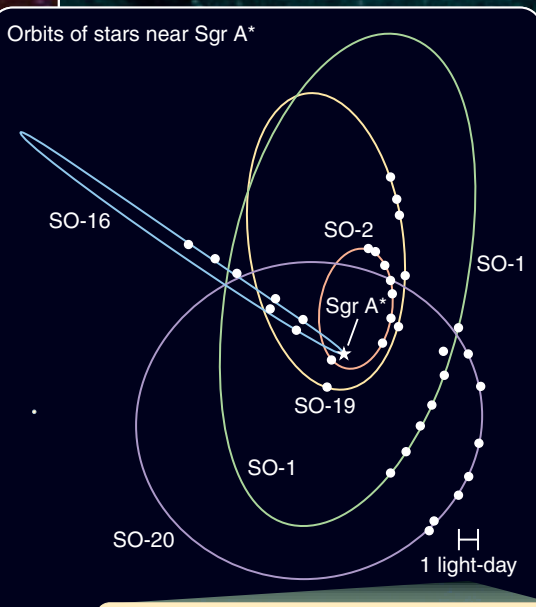
The Chandra X-ray Observatory has imaged Sgr A* and detected over 2000 other X-ray sources in the area.



NASA/CXC/MIT/F.K. Baganoff et al.



Infrared image

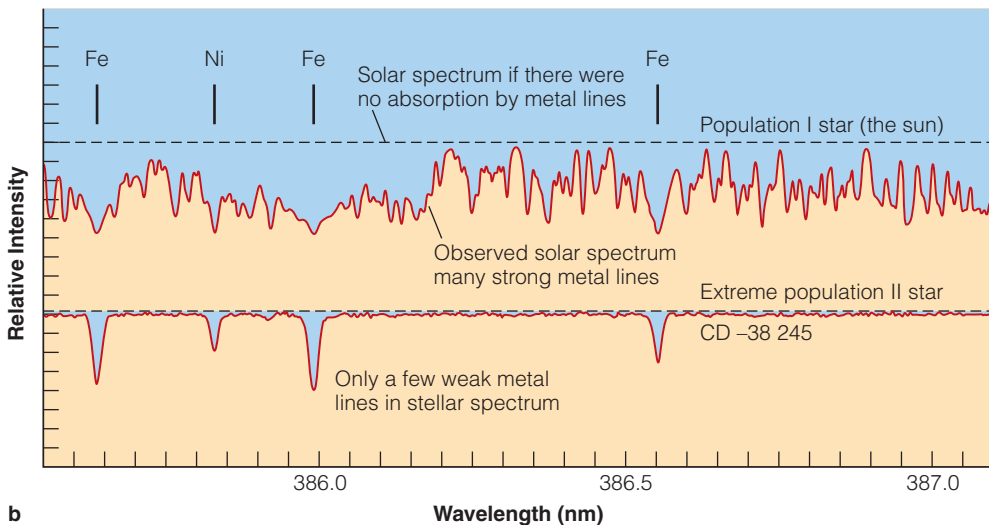
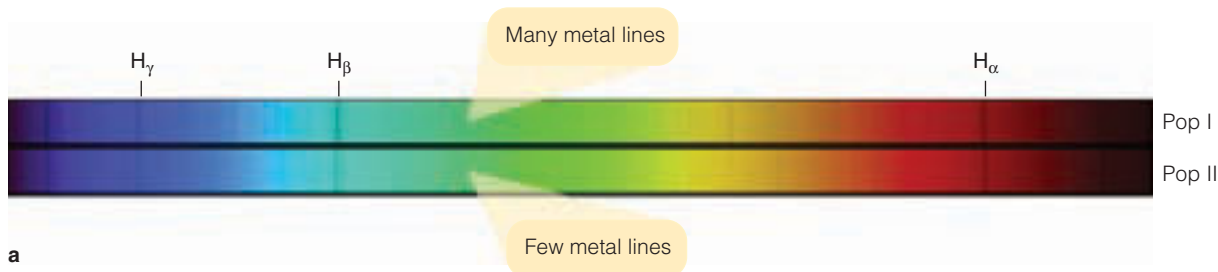


3a A black hole with a mass of 4 million solar masses would have an event horizon with a size on the scale of this diagram smaller than the period at the end of this sentence. A slow dribble of only 0.0002 solar mass of gas per year flowing into the black hole could produce the observed energy. A sudden increase, such as when a star falls in, could produce a violent eruption.

At its closest, SO-2 comes within 17 light-hours of Sgr A*. Alternative theories that Sgr A* is a cluster of stars, of neutron stars, or of stellar black holes are eliminated. Only a single black hole could contain so much mass in so small a region.

For comparison, the diameter of the planetary region of our solar system, defined by Neptune's orbit, is half a light-day.

The evidence of a massive black hole at the center of our galaxy seems conclusive. It is much too massive to be the remains of a dead star, however, and astronomers conclude that it probably formed as the galaxy first took shape.



■ **Figure 15-22**

(a) The difference between spectra of Population I stars and Population II stars is dramatic. Examine the upper spectrum here and notice the hundreds of faint spectral lines. The lower spectrum has fewer and weaker lines. (AURA/NOAO/NSF) (b) A graph of such spectra reveals overlapping absorption lines of metals completely blanketing the Population I spectrum. The lower spectrum is that of an extremely metal-poor star with only a few weak metal lines of iron (Fe) and nickel (Ni). This Population II star contains about 10,000 times less metal than the sun. (Adapted from an ESO illustration)

The two populations of stars in our galaxy are clearly different. They have different chemical compositions, are located in different parts of the galaxy, follow different shaped orbits, and have different ages (■ Table 15-1). These differences are clues to the origin of the galaxy, but to follow those clues you need to consider the origin of the elements.

The Element-Building Process

You can use what you have learned about stellar structure and stellar evolution (Chapters 11 to 13) to understand the origin of the metals. Remember that in astronomy jargon, the term *metals*

refers to all of the chemical elements heavier than helium. When the universe began, it contained only hydrogen and helium atoms. (You will learn about the evidence that supports this statement in Chapter 18.) All of the other chemical elements have been produced by **nucleosynthesis**, the process that fuses hydrogen and helium to make the heavier elements. Telling the story of a process from beginning to end is an important part of science (**How Do We Know? 15-2**).

When our galaxy formed sometime after the beginning of the universe, the gas contained about 90 percent hydrogen atoms, 10 percent helium atoms, and almost no heavier atoms.

■ **Table 15-1** | **Stellar Populations**

	Population I		Population II	
	Extreme	Intermediate	Intermediate	Extreme
Location	Spiral arms	Disk	Central bulge	Halo
Metals (%)	3	1.6	0.8	Less than 0.8
Shape of orbit	Circular	Slightly elliptical	Moderately elliptical	Highly elliptical
Average age (yr)	100 million and younger	0.2–10 billion	2–10 billion	10–13 billion

Nature as Processes

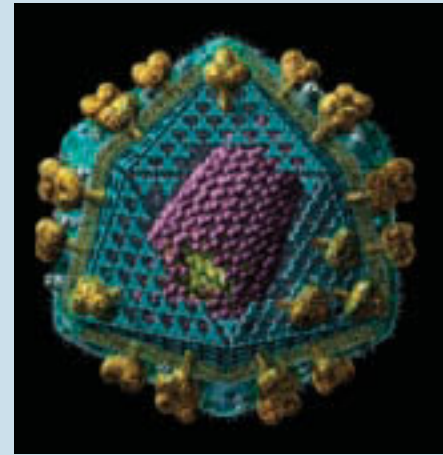
How is getting a cold like stars building the chemical elements? Science, at first glance, seems to be nothing but facts; but, in many cases, you can organize the facts into the story of a process. For example, astronomers try to assemble the sequence of events that led to the formation of the chemical elements. If you understand that process, you have command over a lot of important facts in astronomy.

A process is a sequence of events that leads to some result or condition, and much of science is focused on understanding how these natural processes work. Biologists, for example, try to understand how a virus reproduces. They must figure out how the virus tricks the immune system to leave it alone, penetrates the wall of a healthy cell, injects viral DNA, commandeers the cell's resources to make new viruses, and finally destroys the cell

to release the new virus copies. A biologist may spend her life studying a specific step, but the ultimate goal of science is to tell the entire story of the process.

As you study any science, be alert for processes as organizing themes. When you see a process in science, ask yourself a few basic questions. What conditions prevailed at the beginning of the process? What sequence of steps occurred? Can some steps occur simultaneously, or must one step occur before another can occur? What is the final state that this process produces?

Recognizing a process and learning to tell its story will help you remember a lot of details, but that is not the real value of a scientific process. Identifying a process and learning to tell its story helps you understand how nature works and explains why the universe is the way it is.



A virus is a collection of molecules that cannot reproduce until it penetrates into a living cell.
(Russell Knightly Media, rkm.com.au)

Therefore, the first stars to form had to be metal poor. Succeeding generations of stars manufactured heavier atoms, and the metal abundance of the galaxy gradually increased.

As you learned in Chapters 12 and 13, medium-mass stars like the sun cannot ignite carbon fusion; but, during helium shell fusion, the heat and density can trigger low-level nuclear reactions that cook the gas to produce small amounts of elements heavier than helium. When the aging star pushes away its surface layers to produce a planetary nebula, some of those elements are spread back into the interstellar medium.

The most massive stars fuse elements up to iron and simultaneously cook the gas in their cores to produce small amounts of many different atoms, including sulfur and calcium. When those stars die in supernova explosions, traces of those elements are spread back into the interstellar medium. Furthermore, the supernova explosion itself can fuse nuclei into atoms much heavier than iron. These rare atoms, such as gold, platinum, and uranium, also get spread back into space where they may become part of newly forming stars and planets.

Metals are actually quite rare in the universe. Traditionally, astronomers graph the abundance of the elements using an exponential scale, but if you replot the data using a linear scale, you can see how rare these atoms are (■ Figure 15-23).

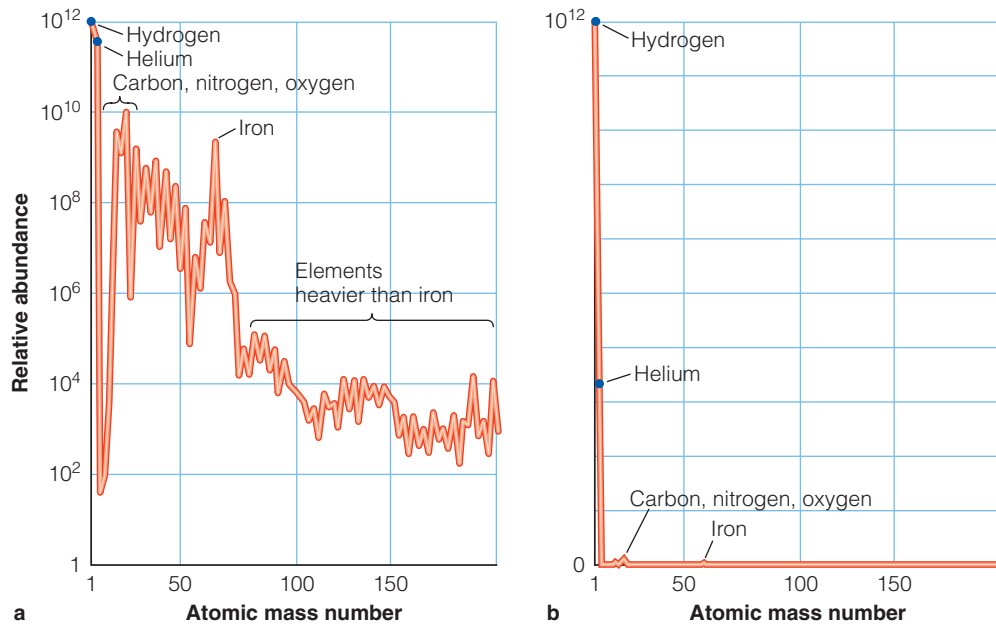
When you observe Population II stars, such as those in the halo, you are looking at the survivors of the early generations of

stars in our galaxy. The first stars formed from gas that was metal poor, and the survivors of these early generations are low-mass, long-lived stars. Their spectra, which indicate the composition of their atmospheres and not their cores, still show the composition of the metal-poor gas from which they formed. Population I stars such as the sun formed more recently, after the interstellar medium had been enriched in metals, and their spectra show stronger metal lines. Stars forming now show even stronger metal lines.

Galactic Fountains

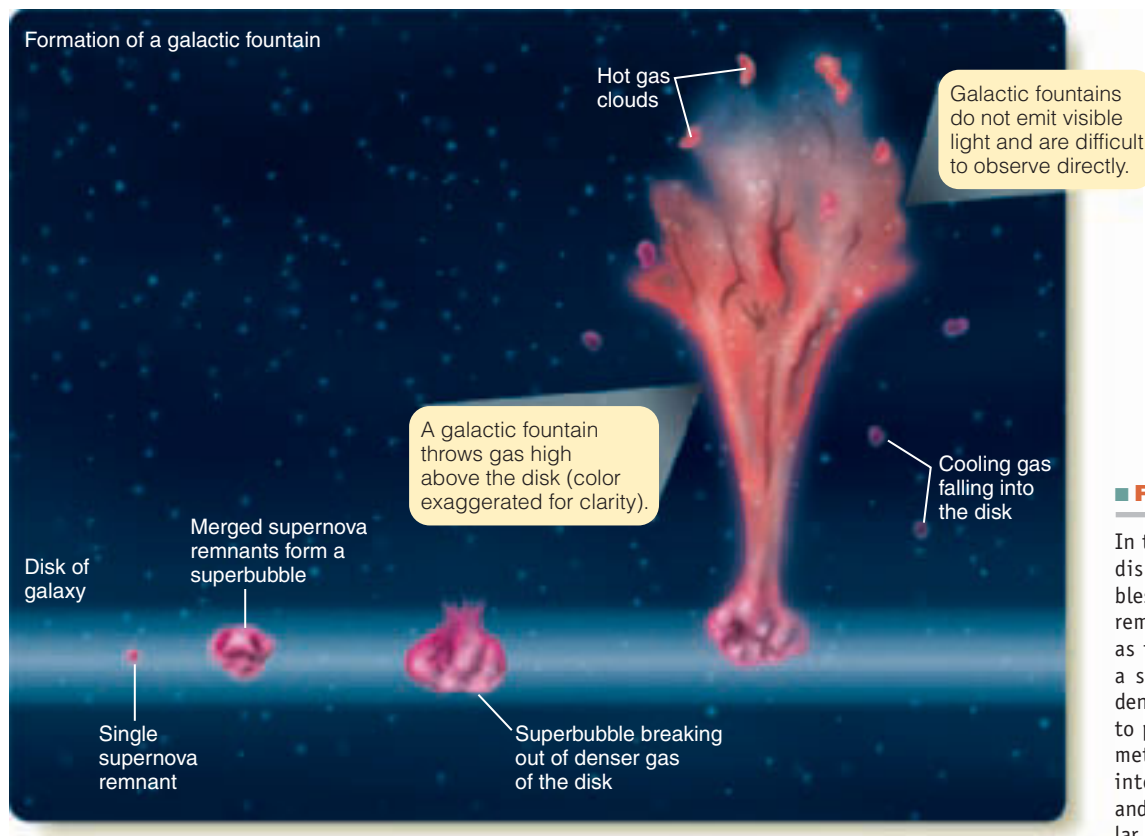
Supernova remnants are rich in metals and eventually mix back into the interstellar medium. In fact, supernovae continuously stir and enrich the interstellar medium. But a larger-scale process may be even more efficient at spreading newly created metals throughout the disk of the galaxy where they can be incorporated into the newly forming stars.

In Chapter 10, you saw how neighboring supernova remnants can merge to form a superbubble of hot gas (Figure 10-9b). A supernova remnant may be only a few tens of parsecs in diameter, but a superbubble can be more than ten times bigger. The denser gas of the galactic disk tends to confine an expanding superbubble, but the disk is only a few hundred parsecs thick. If a superbubble breaks out of the denser gas of the galactic disk, it can spew hot gas high above the plane of the galaxy in a **galactic**



■ **Figure 15-23**

The abundance of the elements in the universe. (a) When the elemental abundances are plotted on an exponential scale, you see that elements heavier than iron are about a million times less common than iron and that all elements heavier than helium (“metals”) are quite rare. (b) The same data plotted on a linear scale provide a more realistic impression of how rare the metals are. Carbon, nitrogen, and oxygen make small peaks near atomic mass 15, and iron is just visible in the graph.



■ **Figure 15-24**

In this edge-on view of the galactic disk, you can see that superbubbles, formed of multiple supernova remnants, can be roughly as large as the thickness of the disk. Once a superbubble breaks out of the denser gas of the disk, it is believed to produce a galactic fountain. The metal-enriched gas could flow out into the halo where it would cool and fall back to enrich the interstellar medium in metals.

fountain (■ Figure 15-24). As this gas cools and falls back into the disk, it can spread metals through the galaxy.

Galactic fountains are difficult to observe directly, but isolated clouds of gas have been found high in the halo, and cool clouds have been found falling toward the disk. Some of these

may be material from outside the galaxy that is falling inward for the first time, but the lower-velocity clouds only a few thousand parsecs above the disk may be cooling gas that was spewed out of the disk by fountains. It seems likely that this process contributes to spreading metals through the disk. Either way, it is evident

that supernovae create metals and mix them back into the interstellar medium where they can be incorporated into newly forming stars.

Because the recycling of stellar nucleosynthesis products means that the metal abundance of newborn stars increases as the galaxy ages, astronomers can use metal abundance as an index to the ages of the components of our galaxy. The halo is old, and the disk is younger.

The Age of the Milky Way

Because astronomers know how to find the age of star clusters, they can estimate the age of our galaxy. The process sounds straightforward, but uncertainties make the easy answer hard to interpret.

The oldest open clusters are 9 to 10 billion years old. These ages come from the turnoff points in their H–R diagrams (see Chapter 12), but finding the age of an old cluster is difficult because old clusters change so slowly. Also, the exact location of the turnoff point depends on chemical composition, which differs slightly among clusters. Finally, open clusters are not strongly bound by their gravity, so older open clusters may have dissipated as their stars wandered away. It is reasonable to suppose that the galactic disk is somewhat older than the oldest remaining open clusters, which suggests that the disk is at least 10 billion years old.

Globular clusters have faint turnoff points in their H–R diagrams and are clearly old, but finding these ages is difficult. Again, slight differences in chemical composition make noticeable differences when calculating the stellar models from which ages are determined. Also, to find the age of a cluster, astronomers must know its distance. Precise parallaxes from the Hipparcos satellite have allowed astronomers to more accurately calibrate the Cepheid and RR Lyrae variable stars, and careful studies with the newest large telescopes have refined the chemical compositions and better defined the H–R diagrams of globular clusters. The best analysis of all of the data suggests that the average globular clusters are about 11 billion years old, although some globular clusters are younger than that, and some are older. Studies of the oldest globular clusters suggest that the halo of our galaxy is at least 13 billion years old.

Observations of stellar populations and clusters show that the disk is younger than the halo. You can combine these ages with the process of nucleosynthesis to tell the story of our galaxy.

Formation of the Galaxy

The lack of metals in the spherical component of the galaxy tells you it is very old, a fossil left behind by the galaxy when it was young and drastically different from its present disk shape. The study of element building and stellar populations leads to the fundamental question, “How did our galaxy form?”

In the 1950s, astronomers began to develop a hypothesis sometimes called the **monolithic collapse hypothesis** to explain the formation of our galaxy. Recent observations, however, are forcing a major revision of that hypothesis.

The monolithic collapse hypothesis says that the galaxy formed from a single large cloud of turbulent gas over 13 billion years ago. That cloud contracted to form our galaxy. As gravity pulled the gas inward, the cloud began to fragment into smaller clouds; and, because the gas was turbulent, the smaller clouds had random velocities. That caused the stars and star clusters that formed from these fragments to have orbits with a wide range of shapes; a few were circular, most were elliptical, and some were extremely elliptical. The orbits were also inclined at different angles, resulting in a spherical cloud of stars—the spherical component of the galaxy. Of course, these first stars were metal poor because no stars had existed earlier to enrich the gas with metals.

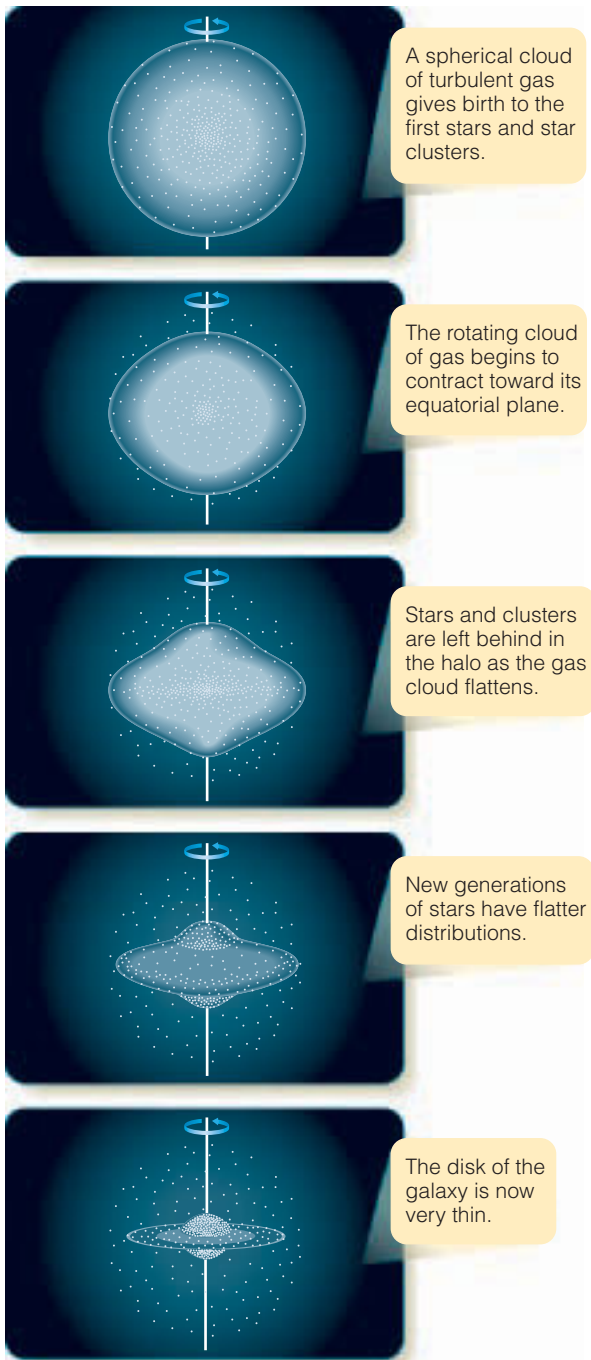
The second stage in this hypothesis accounts for the formation of the disk component. As the gas clouds in the originally spherical cloud collided, turbulent motions in the gas canceled out, as do eddies in recently stirred coffee, and the cloud was left with a uniform rotation. A rotating, low-density cloud of gas cannot remain spherical. A star is spherical because its high internal pressure balances its gravity; but, in a low-density cloud, the internal pressure is much too low to support the weight. Like a blob of pizza dough spun in the air, the cloud must flatten into a disk (■ Figure 15-25), eventually producing the galaxy’s disk.

This contraction from a sphere into a disk must have taken billions of years, and while that happened the metal abundance gradually increased as generations of stars were born from the gradually flattening gas cloud. The stars and globular clusters of the halo were left behind by the cloud as it flattened, and subsequent generations of stars formed in flatter distributions. The gas distribution in the galaxy now is so flat that the youngest stars are confined to a disk only about 100 parsecs thick. These stars are metal rich and have nearly circular orbits.

The monolithic collapse hypothesis accounts for many of the Milky Way’s properties. Advances in technology, however, have improved astronomical observation, and, beginning in the 1980s, contradictions between theory and observation arose. For example, not all globular clusters have the same age, but, surprisingly, some of the youngest clusters seem to be in the outer halo. In contrast, the monolithic collapse hypothesis says that the halo formed first and predicts that the clusters within it should either have a uniform age or the most distant ones should be slightly older. Another problem is that the oldest stars are observed to be metal poor but not completely metal free. There must have been at least a few massive stars to create these metals during a generation before the formation of the oldest stars now seen in the halo.

Can the original hypothesis be modified to explain these observations? Astronomers suspect that the galaxy began as a

Origin of the Halo and Disk



■ **Figure 15-25**

The “monolithic collapse” model for the origin of our galaxy begins with a spherical gas cloud that flattens into a disk.

large gas cloud containing almost no metals. Models of metal-free stars show that they are very massive, so that first generation of stars evolved rapidly and exploded as supernovae, which enriched the gas cloud with traces of metals. None of those massive first-generation stars survive, but the metals they created are detectable in the oldest Population II stars.



■ **Figure 15-26**

The Large and Small Magellanic clouds, shown here rising above the Walter Baade Telescope’s dome at the Magellan Observatory in Chile, are small galaxies that orbit close to the Milky Way Galaxy. A long trail of stars and gas stretching halfway around the sky reveals that they are being ripped apart, and the Milky Way Galaxy is absorbing their stars, gas, and dust. (Kris Koenig/Coast Learning Systems)

It seems likely that the central bulge and halo formed from such a gas cloud or from the accumulation of a number of gas clouds. A thick but low-density disk of stars may have formed at this early stage. This would explain the age of the central bulge and the metals in both the oldest stars in the halo and those scattered above and below the disk. The thin part of the disk could have formed later as more gas fell into the galaxy and settled into the gas clouds of the disk where the stars are forming today.

Perhaps entire galaxies were captured by the growing Milky Way Galaxy. Astronomers have found streams and rings of scattered stars surrounding our galaxy and suspect they were produced when smaller galaxies were captured, pulled apart, and absorbed by our home galaxy (■ Figure 15-26). You will see dramatic evidence in the next chapter that such galaxy mergers do occur.

If the young Milky Way Galaxy absorbed a few small but partially evolved galaxies, then some of the globular clusters astronomers see in the halo may be hitchhikers. This would explain the range of globular cluster ages. In fact, some astronomers hypothesize that our galaxy formed through a rapid merger of a number of smaller pregalaxy clouds of gas and stars with later additions of infalling gas and other small galaxies.

The problem of the formation of our galaxy is frustrating because the hypotheses are incomplete. Almost everyone prefers certainty to confusion, but astronomers are still gathering observations and testing hypotheses. The older monolithic collapse hypothesis has proven inadequate to explain all of the observations, and astronomers are attempting to refine the observations and devise new theories. The metal abundances and ages of the stars in our galaxy seem to be important clues, but metal abundance and age do not tell the whole story. Astronomer Bernard Pagel was thinking of this when he said, “Cats and dogs may have the same age and metallicity, but they are still cats and dogs.”

SCIENTIFIC ARGUMENT

Why do metal-poor stars have the most eccentric orbits?

A good argument makes connections between ideas, and sometimes those connections are not obvious. Certainly, the metal abundance of a star cannot affect its orbit, so an analysis must not confuse cause and effect with the relationship between these two factors. Both chemical composition and orbital shape depend on a third factor—age. The oldest stars are metal poor because they formed before there had been many supernova explosions to create and scatter metals into the interstellar medium. Those stars formed long ago when the galaxy was young and motions were not organized into a disk, so the stars tended to take up randomly shaped orbits, many of which are quite elongated and eccentric. Consequently, today, the most metal-poor stars tend to follow the most eccentric orbits.

Nevertheless, even the oldest stars known in our galaxy contain some metals. They are metal poor, not metal free. Adjust your argument. **Where did these metal-poor stars get their metals?**

What Are We? Children of the Milky Way

Hang on tight. The sun, with Earth in its clutch, is ripping along at about 220 km/s (that's 490,000 mph) as it orbits the center of the Milky Way Galaxy. We live on a wildly moving ball of rock in a large galaxy that humanity calls home, but the Milky Way is more than just our home. Perhaps “parent galaxy” would be a better name.

Except for hydrogen atoms, which have survived unchanged since the universe began, you and Earth are made of

metals—atoms heavier than helium. There is no helium in your body, but there is plenty of carbon, nitrogen, and oxygen. There is calcium in your bones and iron in your blood. All of those atoms and more were cooked up inside stars or in their supernova deaths.

Stars are born in the galaxy's disk when clouds of gas orbiting the center of the galaxy collide with the gas in spiral arms and are compressed. That process has

given birth to generations of stars, and each generation has produced elements heavier than helium and spread them back into the interstellar medium. The abundance of metals has grown slowly in the galaxy. About 4.6 billion years ago a cloud of gas enriched in those heavy atoms slammed into a spiral arm and produced the sun, Earth, and you. You have been cooked up by the Milky Way—your parent galaxy.

Study and Review

Summary

- ▶ The hazy band of the Milky Way is our wheel-shaped galaxy seen from within, but its size and shape are not obvious. William and Caroline Herschel counted stars at many locations over the sky to show that our star system seemed to be shaped like a grindstone with the sun near the center.
- ▶ Later astronomers studied the distributions of stars, but because gas and dust in space blocked their view of distant stars, they concluded the star system was only about 10 **kiloparsecs (p. 303)** in diameter with the sun at the center.
- ▶ In the early 20th century, Harlow Shapley **calibrated (p. 306)** Cepheid variable stars to find the distance to globular clusters, demonstrating that our galaxy is much larger than what we can see and that the sun is not at the center.
- ▶ Modern observations suggest that our galaxy contains a **disk component (p. 308)** about 80,000 ly in diameter and that the sun is two-thirds of the way from the center to the visible edge. The **central bulge (p. 309)** around the center and an extensive **halo (p. 309)** containing old stars and little gas and dust make up the **spherical component (p. 309)**.
- ▶ The mass of the galaxy can be found from its **rotation curve (p. 311)**. Kepler's third law reveals that the galaxy contains at least 100 billion solar masses. If stars orbited in **Keplerian motion (p. 311)**, more distant stars would orbit more slowly. They do not, and that shows that the halo must contain much more mass than is visible. Because the mass in this **galactic corona (p. 311)** is not emitting detectable electromagnetic radiation, astronomers call it **dark matter (p. 311)**.
- ▶ You can trace the spiral arms through the sun's neighborhood by using **spiral tracers (p. 313)** such as OB associations; but, to extend the map over the entire galaxy, astronomers must use radio telescopes to see through the gas and dust.
- ▶ The most massive stars live such short lives they don't have time to move from their place of birth. Because they are found scattered along the spiral arms, astronomers conclude that the spiral arms are sites of star formation.
- ▶ The spiral **density wave theory (p. 315)** suggests that the spiral arms are regions of compression that move around the disk. When an orbiting gas cloud overtakes the compression wave, the gas cloud is compressed and forms stars. A density wave produces a two-armed **grand-design (p. 316)** spiral galaxy.
- ▶ Another process, **self-sustaining star formation (p. 316)**, may act to modify the arms with branches and spurs as the birth of massive stars triggers the formation of more stars by compressing neighboring gas clouds. This may account for the woolly appearance of **flocculent (p. 316)** galaxies.
- ▶ The nucleus of the galaxy is invisible at visual wavelengths, but radio, infrared, and X-ray radiation can penetrate the gas and dust. These wavelengths reveal crowded central stars and warmed dust.
- ▶ The very center of the Milky Way Galaxy is marked by a radio source, **Sagittarius A* (p. 318)**. The core must be less than an astronomical unit in diameter, but the motions of stars around the center show that it must contain roughly 4 million solar masses. A supermassive black hole is the only object that could contain so much mass in such a small space.
- ▶ The oldest star clusters reveal that the disk of our galaxy is younger than the halo, and the oldest globular clusters appear to be about 13 billion years old. So our galaxy must have formed about 13 billion years ago.

- ▶ Stellar populations are an important clue to the formation of our galaxy. The first stars to form, termed **Population II stars (p. 319)**, were poor in elements heavier than helium—elements that astronomers call **metals (p. 319)**. As generations of stars manufactured metals in a process called **nucleosynthesis (p. 322)** and spread them back into the interstellar medium, the metal abundance of more recent generations increased. **Population I stars (p. 319)**, including the sun, are richer in metals.
- ▶ **Galactic fountains (p. 323–324)** produced by expanding supernova remnants may help spread metals throughout the disk.
- ▶ Because the halo is made up of Population II stars and the disk is made up of Population I stars, astronomers conclude that the halo formed first and the disk later.
- ▶ The **monolithic collapse hypothesis (p. 325)**, that the galaxy formed from a single, roughly spherical cloud of gas and gradually flattened into a disk, does not match all of the current evidence and has been amended to include mergers with other galaxies and infalling gas contributing to the disk.

Review Questions

1. Why is it difficult to specify the dimensions of the disk and halo?
2. Why didn't astronomers before Shapley realize how large the galaxy is?
3. What evidence can you cite that our galaxy has a massive corona?
4. Explain why some star clusters lose stars more slowly than others.
5. Contrast the motion of the disk stars and that of the halo stars. Why do their orbits differ?
6. Why are metals less abundant in older stars than in younger stars?
7. Why do metal-poor stars have a wider range of orbital shapes than metal-rich stars like the sun?
8. What evidence contradicts the monolithic collapse hypothesis for the origin of our galaxy?
9. Why are all spiral tracers young?
10. Why couldn't spiral arms be physically connected structures? What would happen to them?
11. What kind of galaxy would the spiral density wave produce if it acted alone?
12. Why does self-sustaining star formation produce clouds of stars that look like segments of spiral arms?
13. Describe the kinds of observations you would make to study the galactic nucleus.
14. Why must astronomers use infrared telescopes to observe the motions of stars around Sgr A*?
15. What evidence can you cite that the nucleus of the galaxy contains a supermassive energy source that is very small in size?
16. **How Do We Know?** Calibration simplifies complex measurements, but how does that make the work of later astronomers dependent on the expertise of the astronomer who did the calibration?
17. **How Do We Know?** The story of a process makes the facts easier to remember, but that is not the true goal of the scientist. What is the real value of understanding a scientific process?

Discussion Questions

1. How would this chapter be different if interstellar dust did not scatter light?
2. Why doesn't the Milky Way circle the sky along the celestial equator or the ecliptic?

Problems

1. Make a scale sketch of our galaxy in cross section. Include the disk, sun, nucleus, halo, and some globular clusters. Try to draw the globular clusters to scale.
2. Because of dust, astronomers can see only about 5 kpc into the disk of the galaxy at visual wavelengths. What percentage of the galactic disk does that include? (*Hint*: Consider the area of the entire disk versus the area visible from Earth.)
3. The fastest passenger aircraft, the Concorde, could fly 0.59 km/s (1320 mph). How long would it take to reach the sun? The galactic center? (*Hint*: $1 \text{ pc} = 3.1 \times 10^{13} \text{ km}$.)
4. If a typical halo star has an orbital velocity of 250 km/s, how long does it take to pass through the disk of the galaxy? Assume that the disk is 1000 pc thick.
5. If the RR Lyrae stars in a globular cluster have apparent magnitudes of 14, how far away is the cluster? (*Hints*: Use the magnitude-distance formula, and see Figure 12-14.)
6. If interstellar dust makes an RR Lyrae variable star look 1 magnitude fainter than it should, by how much will you overestimate its distance? (*Hint*: Use the magnitude-distance formula or Table 9-1.)
7. If a globular cluster is 10 arc minutes in diameter and 8.0 kpc away, what is its diameter? (*Hint*: Use the small-angle formula, Chapter 3.)
8. If you assume that a globular cluster 4.0 arc minutes in diameter is actually 25 pc in diameter, how far away is it? (*Hint*: Use the small-angle formula, Chapter 3.)
9. If the sun is 4.6 billion years old, how many times has it orbited the galaxy?
10. If the true distance to the center of the galaxy is 7 (instead of 8) kpc and the orbital velocity of the sun is 220 km/s, what is the minimum mass of the galaxy? (*Hint*: Use Kepler's third law.)
11. What temperature would interstellar dust have to have to radiate most strongly at $100 \mu\text{m}$? (*Hint*: $1 \mu\text{m} = 1000 \text{ nm}$. Use Wien's law, Chapter 7.)
12. Infrared radiation from the center of our galaxy with a wavelength of about $2 \mu\text{m}$ ($2 \times 10^{-6} \text{ m}$) comes mainly from cool stars. Use this wavelength as λ_{max} and find the temperature of the stars.
13. If an object at the center of our galaxy has a linear diameter of 10 AU, what will its angular diameter be as seen from Earth? (*Hint*: Use the small-angle formula, Chapter 3.)

Learning to Look

1. Why does the galaxy shown at the right have so much dust in its disk? How big do you suppose the halo of this galaxy really is?



NASA/Hubble Heritage Team/STScI/AURA

2. Why are the spiral arms in the galaxy at the right blue? What color would the halo be if it were bright enough to see in this photo?



NASA/Hubble Heritage Team and A. Riess, STScI



Visual wavelength image

Guidepost

Our Milky Way Galaxy is only one of the many billions of galaxies visible in the sky. This chapter will expand your horizon to discuss the different kinds of galaxies and their complex histories. Here you can expect answers to five essential questions:

— **What do galaxies look like?**

— **How do astronomers measure the distances to galaxies?**

— **How do galaxies differ in size, luminosity, and mass?**

— **Do other galaxies contain supermassive black holes and dark matter, as does our galaxy?**

— **Why are there different kinds of galaxies?**

As you begin studying galaxies, you will discover they are classified into different types, and that will lead you to insights into how galaxies form and evolve. In the next chapter, you will discover that some galaxies are violently active, and that will give you more clues to the evolution of galaxies.

Even if your spaceship could travel at the speed of light, it would take you 29 million years to reach the Sombrero Galaxy, also known as M104, one of the closest galaxies to our Milky Way Galaxy. (NASA/ESA/Hubble Heritage Team/STScI/AURA)

A hypothesis or theory is clear, decisive, and positive, but it is believed by no one but the man who created it. Experimental findings, on the other hand, are messy, inexact things which are believed by everyone except the man who did that work.

— HARLOW SHAPLEY, *THROUGH RUGGED WAYS TO THE STARS*

SCIENCE FICTION HEROES FLIT EFFORTLESSLY between the stars, but almost none travels between the galaxies. As you leave your home galaxy, the Milky Way, behind, you will voyage out into the depths of the universe, out among the galaxies, into space so deep it is unexplored even in fiction.

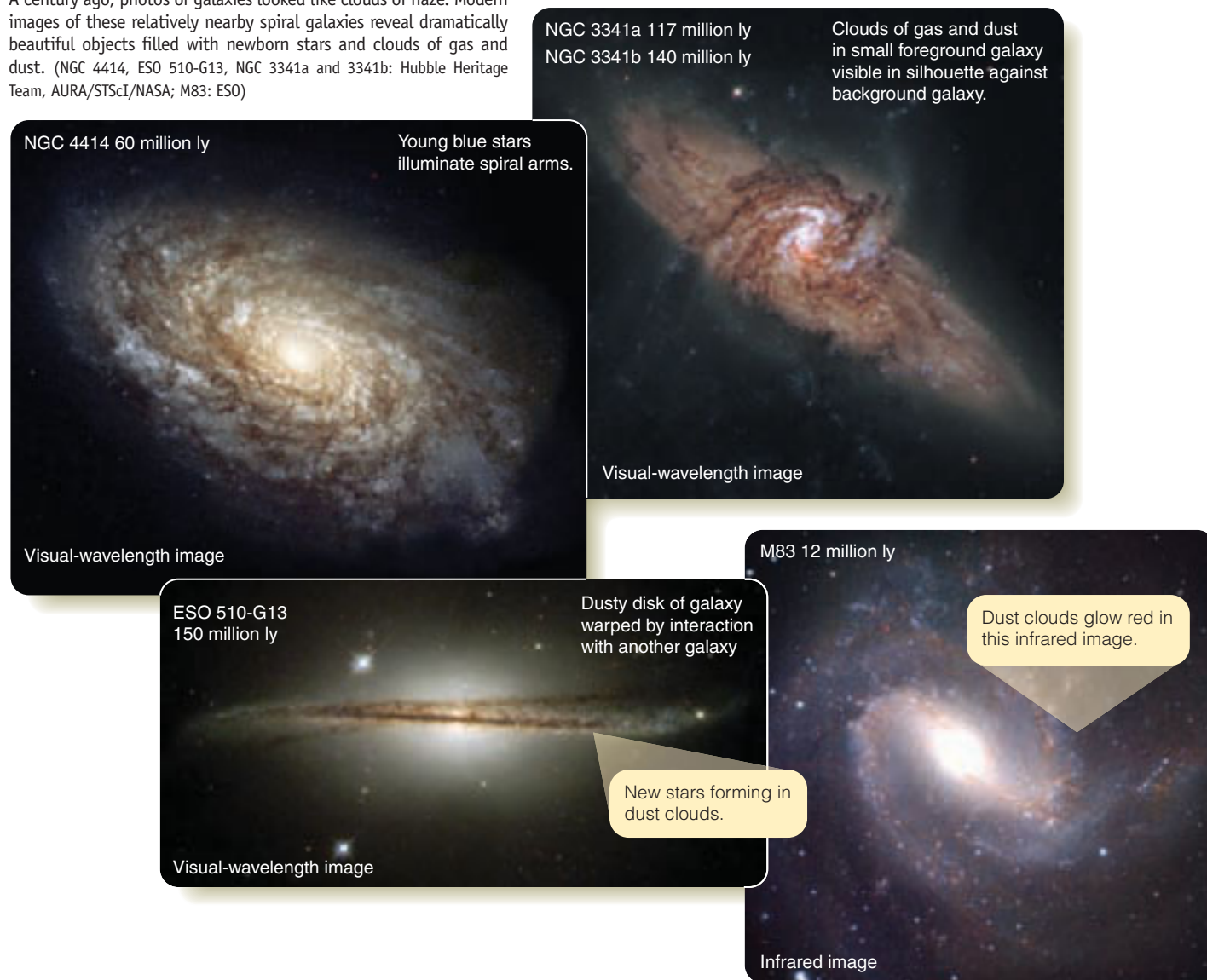
■ Figure 16-1

A century ago, photos of galaxies looked like clouds of haze. Modern images of these relatively nearby spiral galaxies reveal dramatically beautiful objects filled with newborn stars and clouds of gas and dust. (NGC 4414, ESO 510-G13, NGC 3341a and 3341b: Hubble Heritage Team, AURA/STScI/NASA; M83: ESO)

Before you can begin to understand the life stories of the galaxies, you need to gather some basic data. How many kinds of galaxies are there? How big are they? How massive are they? You can characterize the family of galaxies just as you characterized the family of stars in Chapter 9.

16-1 The Family of Galaxies

LESS THAN A CENTURY AGO, astronomers did not know for certain that there are such things as galaxies. Nineteenth-century telescopes revealed faint nebulae scattered among the stars, and some were spiral shaped. Astronomers argued about the nature of these faint nebulae, but it was not understood until the 1920s that some were other galaxies much like our own; and it was not until recent decades that astronomical telescopes could fully reveal their tremendous beauty and intricacy (■ Figure 16-1).



The Discovery of Galaxies

Galaxies are faint objects, so they were not noticed until telescopes had grown large enough to gather significant amounts of light. In 1845, William Parsons, third Earl of Rosse in Ireland, built a telescope 72 in. in diameter. It was, for some years, the largest telescope in the world. Parsons lived before the invention of astronomical photography, so he had to view the faint nebulae directly at the eyepiece and sketch their shapes. He noticed that some have a spiral shape, and they became known as **spiral nebulae**. Parsons immediately concluded that the spiral nebulae were great spiral clouds of stars. The German philosopher Immanuel Kant in 1755 had proposed that the universe was filled with great wheels of stars that he called **island universes**. Parsons adopted that term for the spiral nebulae.

Not everyone agreed that the spiral nebulae were clouds of stars lying outside our own star system. An alternative point of view was that our Milky Way star system was alone in an otherwise empty universe. Sir William Herschel had counted stars in different directions and concluded that our star system was shaped approximately like a grindstone (see Figure 15-2). Beyond the edge of this grindstone star system, space was supposed to be a limitless void. The spiral nebulae, in this view, were nothing more than whirls of gas and faint stars within our star system.

The debate over the spiral nebulae could not be resolved in the 19th century because the telescopes were not large enough and photographic plates, when they became available in the late 1800s, were not sensitive enough. The spiral nebulae remained foggy swirls even in the best photographs, and astronomers continued to disagree over their true nature. In April 1920, two astronomers debated the issue at the National Academy of Science in Washington, D.C. Harlow Shapley of Mount Wilson Observatory had recently shown that the Milky Way was a much larger star system than had been thought. He argued that the spiral nebulae were just objects within the Milky Way star system. Heber D. Curtis of Lick Observatory argued that the spiral nebulae were island universes far outside the Milky Way star system. Historians of science mark this **Shapley–Curtis debate** as a turning point in modern astronomy, but it was inconclusive. Shapley and Curtis cited the right evidence but drew incorrect conclusions. The disagreement was finally resolved, as is often the case in astronomy, by evidence from a bigger telescope.

On December 30, 1924, Mount Wilson astronomer Edwin Hubble (for whom the Hubble Space Telescope is named) announced that he had taken photographic plates of a few bright galaxies using the new 100-in. telescope. Not only could he detect individual stars in the spiral nebulae, but he could identify some of the stars as Cepheid variables with apparent magnitudes of about 18. For the brightest Cepheids, which are supergiants, to appear that faint, they had to be very distant. This meant that spiral nebulae must be outside the Milky Way star system. They are galaxies, separate from ours, and rivaling ours in size.

How Many Galaxies Are There?

Like leaves on the forest floor, galaxies carpet the sky. Pick any direction in the sky away from the dust and gas of the Milky Way, and you are looking deep into space. Photons that have traveled for billions of years enter your eye, but they are too few to register on your retina. Only the largest telescopes can gather enough light to detect distant galaxies.

When astronomers chose a relatively empty spot on the sky near the Big Dipper and used the Hubble Space Telescope to record an extremely long exposure of 10 days' duration, they found thousands of galaxies crowded into the image. That image, now known as a Hubble Deep Field, contains a few relatively nearby galaxies along with many others that are as much as 10 billion light-years away (■ Figure 16-2).

Since the first Hubble Deep Field was recorded, other deep fields have been imaged in other parts of the sky and at other wavelengths. The GOODS program (Great Observatories Origins Deep Survey) has used the Hubble Space Telescope with other space telescopes such as the Spitzer Space Telescope and the Chandra X-ray Observatory and with some of the largest ground-based telescopes to image selected deep fields. The GOODS images show that the first Hubble Deep Field was not unusual; the entire sky appears to be just as thickly covered with galaxies.

The GOODS study of distant galaxies is especially amazing when you think that, less than a century ago, humanity did not know that we live in a galaxy or that the universe contained other galaxies. Today telescopes are capable of detecting a few hundred billion galaxies, and new, larger telescopes will reveal even more. The discovery of galaxies was one of the turning points in the history of astronomy.

The Shapes of Galaxies

Look at the galaxies in the Hubble Deep Field (Figure 16-2), and you will see galaxies of different shapes. Some are spiral, some are elliptical, and some are irregular. Astronomers classify galaxies according to their shapes in photographs made at visual wavelengths using a system developed by Edwin Hubble in the 1920s. Such systems of classification are a fundamental technique in science (**How Do We Know? 16-1**).

Read **Galaxy Classification** on pages 334–335 and notice three important points and four new terms that describe the main types of galaxies:

- 1 Many galaxies have no disk, no spiral arms, and almost no gas and dust. These *elliptical galaxies* range from huge giants to small dwarfs.
- 2 Disk-shaped galaxies usually have spiral arms and contain gas and dust. Many of these *spiral galaxies* have a central region shaped like an elongated bar and are called *barred*



■ **Figure 16-2**

An apparently empty spot on the sky only 1/30 the diameter of the full moon contains over 1500 galaxies in this extremely long time exposure known as the Northern Hubble Deep Field. Only four stars are visible in this image; they are sharp points of light with diffraction spikes produced by the telescope optics. Presumably the entire sky is similarly filled with galaxies. (R. Williams and the Hubble Deep Field Team, STScI, NASA)

spiral galaxies. (As you learned in Chapter 15, the Milky Way Galaxy is a barred spiral.) A few disk galaxies contain little gas and dust.

3 Finally, notice the *irregular galaxies*, which are generally shapeless and tend to be rich in gas and dust.

The amount of gas and dust in a galaxy strongly influences its appearance. Galaxies rich in gas and dust usually have active star formation and emission nebulae and contain hot, bright stars. That gives these galaxies a blue tint. Galaxies that are poor in gas and dust contain few or none of these highly luminous blue stars and no emission nebulae and consequently look redder and have a much more uniform appearance.

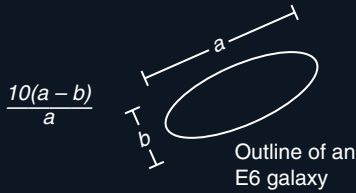
Spiral galaxies are clearly disk shaped, but the true, three-dimensional shape of elliptical galaxies isn't obvious from images. Some are spherical, but the more elongated elliptical galaxies could be shaped like flattened spheres (hamburger bun shaped) or like elongated spheres (American football shaped). Some may even have three different diameters; they are longer than they are thick and thicker than they are wide, like a flattened loaf of bread. Statistical studies suggest that all of these shapes are represented among elliptical galaxies.

Edwin Hubble devised the classification system for galaxies by looking at visual-wavelength images, but infrared images reveal the location of the vast majority of stars—stars that are not as luminous as the hot stars that produce most of the light. These studies suggest that the structures of many galaxies are dominated by the gravitational fields of large masses of low-luminosity cool stars. For example, some spiral galaxies that appear at visible wavelengths to lack bars actually have massive bars that are evident in infrared images. As you think about galaxies, you should remember that their classification is based on where the light comes from and not necessarily where most of the mass is located.

Galaxy Classification

AURA/NOAO/NSF

1 Elliptical galaxies are round or elliptical, contain no visible gas and dust, and have few or no bright stars. They are classified with a numerical index ranging from 1 to 7; E0s are round, and E7s are highly elliptical. The index is calculated from the largest and smallest diameter of the galaxy used in the following formula and rounded to the nearest integer.



The Leo 1 dwarf elliptical galaxy is not many times bigger than a globular cluster.

Anglo-Australian Telescope Board



Visual-wavelength image

M87 is a giant elliptical galaxy classified E1. It is several times larger in diameter than our own galaxy and is surrounded by a swarm of over 500 globular clusters.

2 Spiral galaxies contain a disk and spiral arms. Their halo stars are not visible, but presumably all spiral galaxies have halos. Spirals contain gas and dust and hot, bright O and B stars, as shown at right and below. The presence of short-lived O and B stars alerts us that star formation is occurring in these galaxies. Sa galaxies have larger nuclei, less gas and dust, and fewer hot, bright stars. Sc galaxies have small nuclei, lots of gas and dust, and many hot, bright stars. Sb galaxies are intermediate.

Anglo-Australian Telescope Board

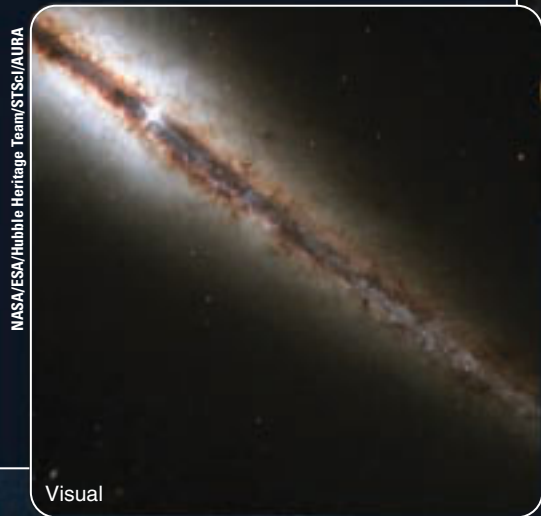


Anglo-Australian Telescope Board



2a Roughly 2/3 of all spiral galaxies are **barred spiral galaxies** classified SBa, SBb, and SBc. They have an elongated nucleus with spiral arms springing from the ends of the bar, as shown at left. Our own galaxy is a barred spiral.

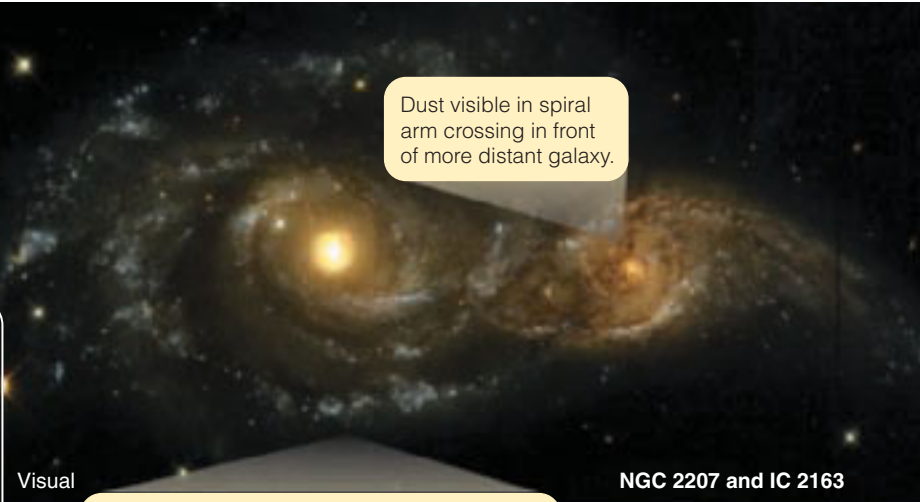
2b Some disk galaxies are rich in dust, which is concentrated along their spiral arms. NGC 4013, shown below, is a galaxy much like ours, but seen edge-on, its dust is dramatically apparent.



NASA/ESA/Hubble Heritage Team/STScI/AURA

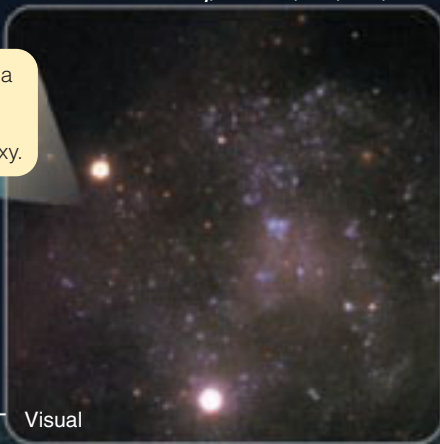
Visual

Dust visible in spiral arm crossing in front of more distant galaxy.



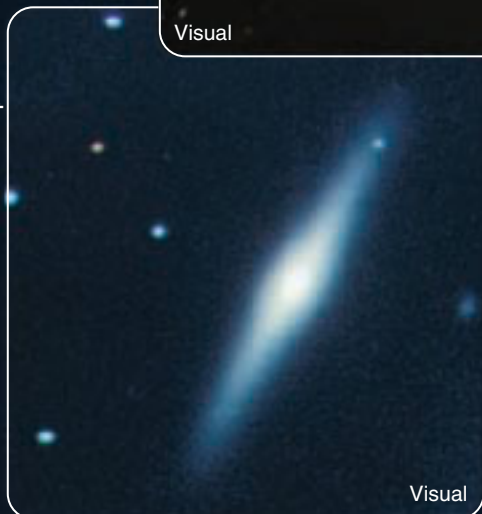
Dust in spiral galaxies is most common in the spiral arms. Here the spiral arms of one galaxy are silhouetted in front of a more distant galaxy.

G. J. Jacoby, M. J. Pierce/AURA/NOAO, NSF



The galaxy IC 4182 is a dwarf irregular galaxy only about 4 million parsecs from our galaxy.

Rudolph E. Schild

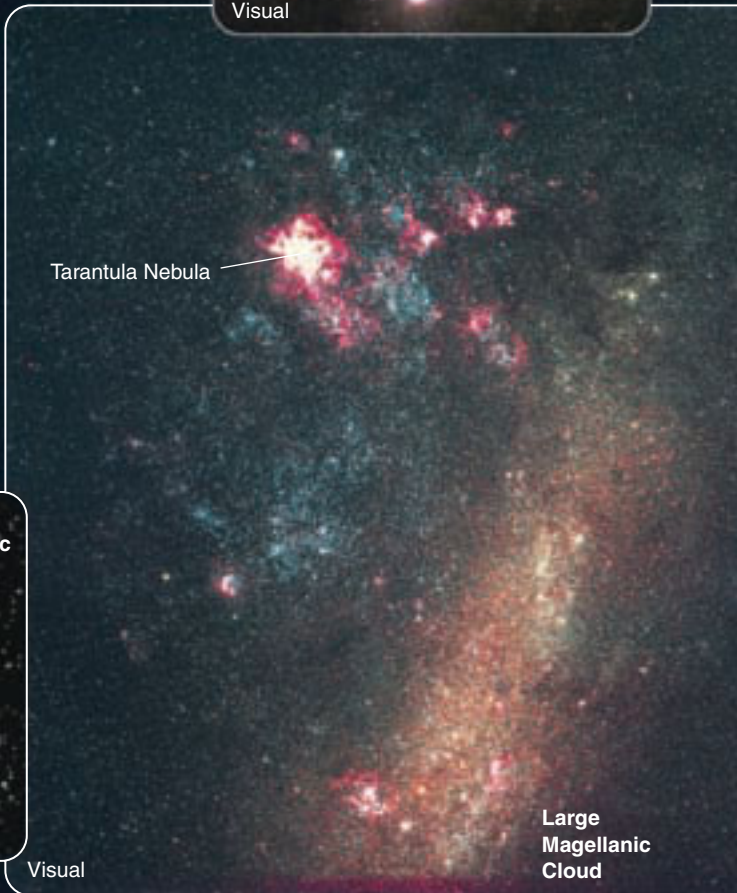


2c Galaxies with an obvious disk and nuclear bulge but no visible gas and dust and few or no hot bright stars are classified as S0 (pronounced "Ess Zero"). Compare this galaxy with the edge-on spiral above.

3 **Irregular galaxies** (classified Irr) are a chaotic mix of gas, dust, and stars with no obvious nuclear bulge or spiral arms. The Large and Small Magellanic Clouds are visible to the unaided eye as hazy patches in the southern hemisphere sky. Telescopic images show that they are irregular galaxies that are interacting gravitationally with our own much larger galaxy. Star formation is dramatic in the Magellanic Clouds. The bright pink regions are emission nebulae excited by newborn O and B stars. The brightest nebula in the Large Magellanic Cloud is called the Tarantula Nebula.



AURA/NOAO/NSF



Classification in Science

What does a flamingo have in common with a *T. rex*? Classification is one of the most basic and most powerful of scientific tools. Establishing a system of classification is often the first step in studying a new aspect of nature, and it can produce unexpected insights.

Charles Darwin sailed around the world from 1831 to 1836 with a scientific expedition aboard the ship *HMS Beagle*. Everywhere he went, he studied the living things he saw and tried to classify them. For example, he classified different types of finches he saw on the Galapagos Islands based on the shapes of their beaks. He found that those that fed on seeds with hard shells had thick, powerful beaks, whereas those that picked insects out of deep crevices had long, thin beaks. His classifications of these and other animals led him to think about how natural selection shapes creatures to survive in their

environment, which led him to understand how living things evolve.

Years after Darwin's work, paleontologists classified dinosaurs into two orders, lizard-hipped and bird-hipped dinosaurs. This classification, based on the shapes of dinosaur hip joints, helped the scientists understand patterns of evolution of dinosaurs. It also led to the conclusion that modern birds, including the finches that Darwin saw on the Galapagos, evolved from dinosaurs.

Astronomers use classifications of galaxies, stars, moons, and many other objects to help them see patterns, trace evolutions, and generally make sense of the astronomical world. Whenever you encounter a scientific discussion, look for the classifications on which it is based. Classifications are the orderly framework on which much of science is built.



The careful classification of living things has revealed that the birds, including this flamingo, are descended from dinosaurs. (M. Seeds)

It is surprisingly difficult to figure out what proportions of galaxies are elliptical, spiral, or irregular. In catalogs of galaxies, about 70 percent are spiral, but that is because spiral galaxies are luminous and easy to notice because they contain hot, bright stars and clouds of ionized gas. Most ellipticals are fainter and

harder to notice. Small galaxies such as dwarf ellipticals and dwarf irregulars are actually very common, but they are hard to detect. From careful statistical studies, astronomers estimate that ellipticals are actually more common than spirals and that irregulars make up only about 25 percent of all galaxies.

Why are there different kinds of galaxies? That is a key question you will explore in the rest of this chapter.

SCIENTIFIC ARGUMENT

What color are galaxies?

Scientific arguments must be based on evidence, and evidence means observations. But you need to be careful and analyze even the simplest observations with care. Different kinds of galaxies have different colors, depending mostly on how much gas and dust they contain. If a galaxy contains large amounts of gas and dust, it probably contains lots of young stars, and a few of those young stars will be massive, hot, luminous O and B stars. They will produce most of the light and give the galaxy a distinct blue tint. In contrast, a galaxy that contains little gas and dust will contain few young stars. It will lack O and B stars, and instead the most luminous stars in such a galaxy will be red giants and supergiants. They will give the galaxy a red tint. Because the light from a galaxy is a blend of the light from billions of stars, the colors are only tints. Nevertheless, the most luminous stars in a galaxy determine the overall color. From this you can conclude that elliptical galaxies tend to be red, and the disks of spiral galaxies tend to be blue.

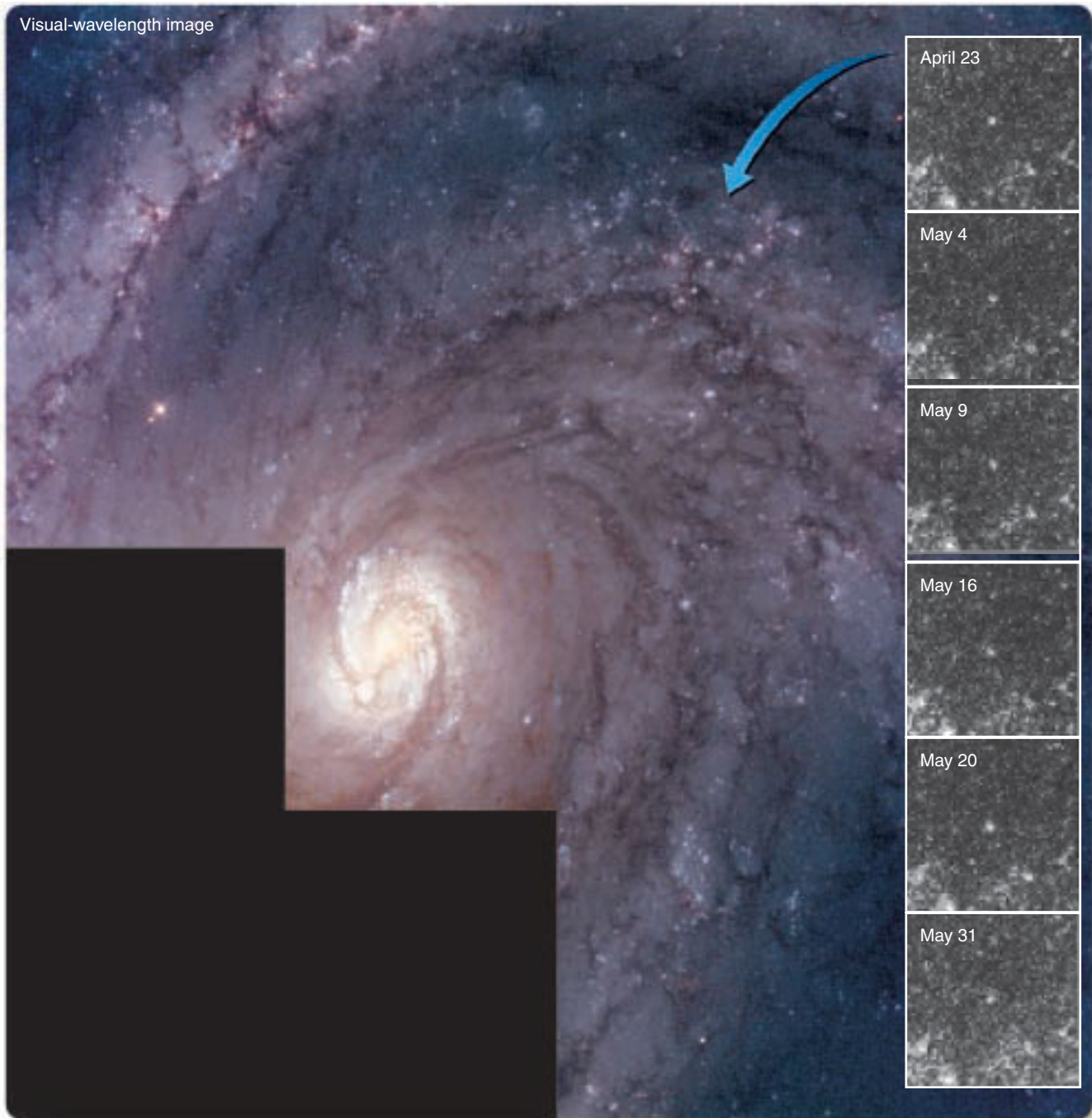
Now create your own scientific argument and analyze a different kind of observation. **Why are most cataloged galaxies spiral in spite of the fact that the most common kind of galaxy is elliptical?**

16-2 Measuring the Properties of Galaxies

LOOKING BEYOND THE EDGE of our Milky Way Galaxy, astronomers find billions of galaxies filling space as far as anyone can see. What are the properties of these star systems? What are the diameters, luminosities, and masses of galaxies? Just as in your study of stellar characteristics (see Chapter 9), the first step in your study of galaxies is to find out how far away they are. Once you know a galaxy's distance, its size and luminosity are relatively easy to find. Later in this section, you will see that, just as for stars, finding the masses of galaxies is more difficult.

Distance

The distances to galaxies are so large that it is not convenient to measure them in light-years, parsecs, or even kiloparsecs. Instead, astronomers use the unit **megaparsec (Mpc)**, or 1 million pc. One Mpc equals 3.26 million ly, or approximately 3×10^{19} km (2×10^{19} miles).



■ **Figure 16-3**

The vast majority of spiral galaxies are too distant for Earth-based telescopes to detect Cepheid variable stars. The Hubble Space Telescope, however, can locate Cepheids in some of these galaxies, as it has in the bright spiral galaxy M100. From a series of images taken on different dates, astronomers can locate Cepheids (inset), determine the period of pulsation, and measure the average apparent brightness. They can then deduce the distance to the galaxy—16 Mpc (52 million ly) for M100. (J. Trauger, JPL; Wendy Freedman, Observatories of the Carnegie Institution of Washington; and NASA)

To find the distance to a galaxy, astronomers must search among its stars, nebulae, and star clusters for familiar objects whose luminosity or diameter they know. Such objects are called **distance**

indicators because they can be used to find the distance to a galaxy. Most distance indicators are objects whose brightness is known, and astronomers often refer to them as **standard candles**. If you can find a standard candle in a galaxy, you can judge its distance.

Cepheid variable stars are reliable distance indicators because their period is related to their luminosity. The period–luminosity relation has been calibrated (see Figure 12-14 as well as “How Do We Know? 15-1”), so you can use the period of the star’s variation to find its absolute magnitude. Then, by comparing its absolute and apparent magnitudes, you can find its distance. ■ Figure 16-3 shows a galaxy in which the Hubble Space Telescope detected Cepheids.

Even with the Hubble Space Telescope, Cepheids are not visible in galaxies much beyond 30 Mpc (100 million ly), so astronomers must search for less common but brighter distance indicators and calibrate them using nearby galaxies that contain both indicators. For example, by studying nearby galaxies with distances known from Cepheids, astronomers have found that the brightest globular clusters have absolute magnitudes of about -10 . If you found globular clusters in a more distant galaxy, you could assume that the brightest of the globular clusters have absolute magnitudes of -10 and use that information to calculate the distance.

Astronomers can use globular clusters in a different way. Studies of nearby globular clusters with known distance show that they are about 25 pc in diameter. If astronomers can detect globular clusters in a distant galaxy, they can assume the clusters are about 25 pc in diameter, measure their angular diameter, and calculate the distance to the galaxy from the small-angle formula. This shows that a distance indicator can be an object of known absolute magnitude or known diameter.

Astronomers can calibrate type Ia supernovae, those produced by the collapse of a white dwarf, because the white dwarf always collapses at the same mass limit, so the explosions reach approximately the same maximum luminosity. When type Ia supernovae occur in galaxies with distances that are known from Cepheid variables and other distance indicators, astronomers can find the absolute magnitude of the supernovae at peak brightness. An example is shown in ■ Figure 16-4. When astronomers see a type Ia supernova in a more distant galaxy, they observe the apparent magnitude of the supernova at maximum and compare that with the known absolute magnitude these supernovae reach at maximum to find the distance to the galaxy. As you will see in Chapter 18, this is a critical calibration in modern measurements of the size and age of the universe.

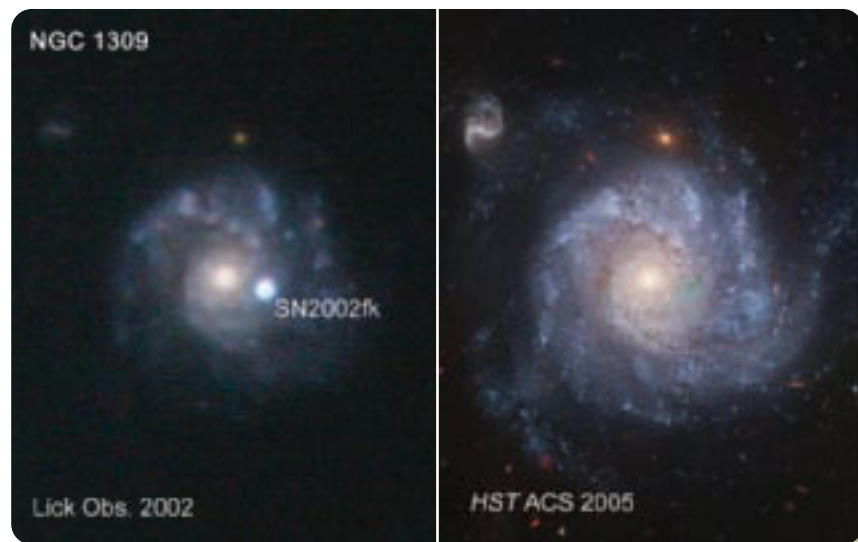
Cepheids and globular clusters are invisible in the most distant galaxies, and supernovae are rare. Consequently, to measure

the greatest distances, astronomers have calibrated the total luminosity of the galaxies themselves. For example, studies of nearby galaxies show that a normal large spiral galaxy like the Milky Way has a luminosity of about 16 billion times that of the sun. If you see a spiral galaxy far away, you can measure its apparent magnitude and estimate its distance. Of course, it is important to recognize the different types of galaxies, and that is difficult to do at great distances, as you can see by looking at the fainter galaxies in Figure 16-2. Averaging the distances to the brightest spiral galaxies in a cluster can reduce the uncertainty in this method.

Notice how astronomers use calibration to build a **distance scale** reaching from the nearest galaxies to the most distant visible galaxies. Often astronomers refer to this as the “distance pyramid” or the “distance ladder” because each step depends on the steps below it. The most dependable step is the Cepheid variable stars, but notice that Cepheid distance indicators depend on astronomers’ understanding of the luminosities of the stars in the H–R diagram, and that rests on a lower step in the ladder—measurements of the parallax of stars. Stellar parallaxes in turn depend on measuring the size of Earth’s orbit around the sun, which finally rests on the bottom step, measuring the size of Earth itself. The distance ladder ultimately connects the size of Earth to the most distant galaxies in the universe.

The most distant visible galaxies are over 3000 Mpc (10 billion ly) away, and at such distances you see an effect akin to time travel. When you look at a galaxy that is millions of light-years away, you do not see it as it is now but as it was millions of years ago when its light began the journey toward Earth. When you look at a distant galaxy, you look back into the past by an amount called the **look-back time**, a time in years equal to the distance in light years the light from the galaxy traveled to reach Earth.

You may have experienced something like a look-back time if you have ever made a long-distance phone call carried by satellite or watched a TV newscaster interview someone via satellite.



■ **Figure 16-4**

While dinosaurs roamed Earth, a white dwarf in the galaxy NGC 1309 collapsed and exploded as a type Ia supernova, and the light from that explosion reached Earth in 2002. Astronomers found Cepheid variable stars in the galaxy, so they can determine that it is 100 million light-years away, and that allowed them to find the absolute magnitude of the supernova at its brightest. By combining observations of many supernovae, astronomers were able to calibrate type Ia supernovae as distance indicators. (Lick: W. Li and A. V. Filippenko, Berkeley; HST: NASA, ESA, The Hubble Heritage Team, STScI/AURA and A. Riess, STScI)

A half-second delay occurs as a radio signal carries a question 23,000 miles out to a satellite then back to Earth, then carries the answer out to the satellite and again back to Earth. That half-second look-back delay can make people hesitate on long-distance phone calls and produces a seemingly awkward delay in TV interviews.

The look-back time to nearby objects is usually not significant. For example, the look-back time across a football field is a tiny fraction of a second. The look-back time to the moon is 1.3 seconds, to the sun only 8 minutes, and to the nearest star a bit over 4 years. The Andromeda Galaxy has a look-back time of over 2 million years, but that is a mere eyeblink in the lifetime of a galaxy. If you look at more distant galaxies, the look-back time becomes an appreciable part of the age of the universe. You will learn about evidence in Chapter 18 that the universe began almost 14 billion years ago. When you look at the most distant visible galaxies, you are looking back over 10 billion years to a time when the universe was significantly different. The look-back time becomes an important factor as you begin to think about the origin and evolution of galaxies.

The Hubble Law

Although astronomers must work carefully to measure the distance to a galaxy, they often estimate such distances using a simple relationship that was first noticed at about the same time astronomers were beginning to understand the nature of galaxies.

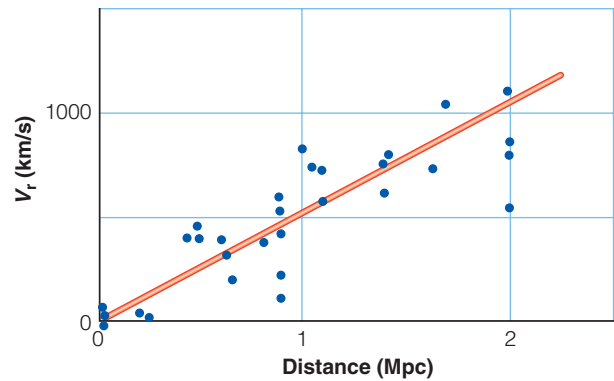
In 1913, Vesto Slipher at Lowell Observatory reported on the spectra of some of the faint, nebulous objects in the sky. Their spectra seemed to be composed of a mixture of stellar spectra: Some had Doppler shifts that suggested rotation; most had redshifts as if they were receding; and the faintest had the largest redshifts. Within two decades, astronomers concluded that the faint objects are galaxies similar to our own Milky Way and that the galaxies are indeed receding from us in a general expansion.

In the 1920s, astronomers Edwin Hubble and Milton Humason were able to measure the distances to a number of galaxies using Cepheid variable stars. In 1929, they published a graph that plotted the apparent velocity of recession versus distance for their galaxies. The points in the graph fell along a straight line (■ Figure 16-5). The straight-line relation from Hubble's diagram can be written as the simple equation

$$V = Hd$$

That is, the apparent velocity of recession V equals the distance d in millions of parsecs times the constant H . This relation between redshift and distance is known as the **Hubble law**, and the constant H is known as the **Hubble constant**. Modern measurements of distance show that H equals about 70 km/s/Mpc.*

* H has the units of a velocity divided by a distance. These are usually written as km/s/Mpc, meaning km per second per Mpc.



■ **Figure 16-5**

Edwin Hubble's first diagram of the apparent velocities of recession and distances of galaxies did not probe very deeply into space, and the vertical axis was later recalibrated. These data did show, however, that the galaxies are receding from one another.

The Hubble law has important implications. It is commonly interpreted to show that the universe is expanding. In Chapter 18, you will study this expansion, but here you can use the Hubble law first as a practical way to estimate the distance to a galaxy.

Simply stated, a galaxy's distance equals its apparent velocity of recession divided by H . For example, if a galaxy has an apparent radial velocity of 700 km/s, and H is 70 km/s/Mpc, then the distance to the galaxy is 700 divided by 70, or about 10 Mpc. This makes it relatively easy to estimate the distances to galaxies because a large telescope can photograph the spectrum of a galaxy and determine its apparent velocity of recession even when it is too distant to have visible distance indicators.

Diameter and Luminosity

Once you find the distance to a galaxy from distance indicators or the Hubble law, you can calculate its diameter and its luminosity. With a good telescope and the right equipment, you could easily photograph a galaxy and measure its angular diameter in arc seconds. If you knew the distance, you could use the small-angle formula (see Chapter 3) to find its linear diameter. If you also measured the apparent magnitude of a galaxy, you could use the magnitude-distance formula to find its absolute magnitude and from that its luminosity (see Chapter 9).

The results of such observations show that galaxies differ dramatically in size and luminosity. Irregular galaxies tend to be small, 1 to 25 percent the size of our galaxy, and of low luminosity. Although they are common, they are easy to overlook. Our Milky Way Galaxy is large and luminous compared with most spiral galaxies, though astronomers know of a few spiral galaxies that are even larger and more luminous. The largest is nearly four times bigger in diameter and about 10 times more luminous. Elliptical galaxies cover a wide range of diameters and luminosities. The largest, called giant ellipticals, are five times the size of



■ **Figure 16-6**

The small galaxy cluster known as Hickson Compact Group 87 appears to contain three spiral galaxies and one elliptical. It is not known whether the small spiral galaxy is in the distant background or is part of the group, but it could be a group member. Note the contrast between the sizes of the galaxies. (Hubble Heritage Team, STScI/AURA/NASA)

our Milky Way, but many elliptical galaxies are very small dwarf ellipticals only 1 percent the diameter of our galaxy.

To put galaxies in perspective, you can use an analogy. If our galaxy were an 18-wheeler, the smallest dwarf galaxies would be the size of pocket-size toy cars, and the largest giant ellipticals would be the size of jumbo jets. Even among spiral galaxies that appeared similar in shape, the sizes could range from that of a go-cart to that of a large bus (■ Figure 16-6).

Clearly, the diameter and luminosity of a galaxy do not determine its type. Some small galaxies are irregular, and some are elliptical. Some large galaxies are spiral, and some are elliptical. Later in this chapter you can build a hypothesis for the origin and evolution of galaxies, but first, you need to add a third basic parameter—mass.

Mass

Although the mass of a galaxy is difficult to determine, it is an important quantity. It tells you how much matter the galaxy contains, which in turn provides clues to the galaxy's origin and evolution. In this section, you will examine two fundamental ways to find the masses of galaxies.

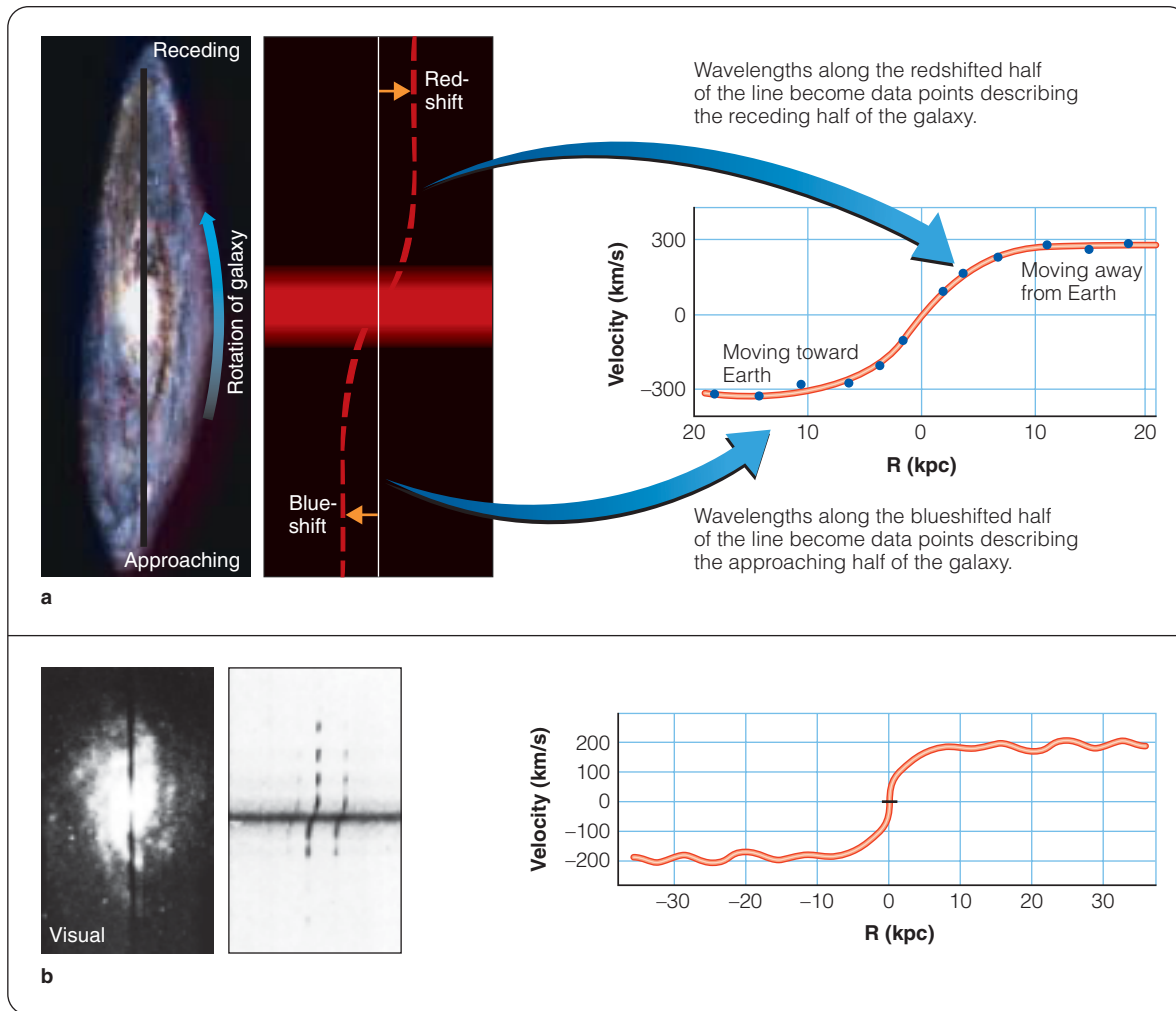
One way to find the mass of a galaxy is to watch it rotate. All you need to know is the radius of the galaxy (in AU) and the orbital period (in years) of the stars orbiting at the galaxy's outer edge. Then you can use Newton's version of Kepler's third law to find the mass, just as you found the mass of binary stars in Chapter 9.

Of course, you don't live long enough to see a galaxy rotate, so you must find the stars' orbital periods using a chain of inference. You could find the orbital velocity of the stars from the Doppler effect. If you focus the image of the galaxy on the slit of a spectrograph, you see a bright spectrum formed by the bright nucleus of the galaxy, in addition to fainter emission lines produced by ionized gas in the disk of the galaxy. Because the galaxy rotates, one side moves away from Earth and one side moves toward Earth, so the emission lines would be redshifted on one side of the galaxy and blueshifted on the other side. You could measure those changes in wavelength, use the Doppler formula to find the velocities, and plot a diagram showing the velocity of rotation at different distances from the center of the galaxy—a diagram called a **rotation curve**. The artwork in ■ Figure 16-7a shows the process of creating a rotation curve, and Figure 16-7b shows a real galaxy, its spectrum, and its rotation curve.

Of course, once you know the orbital velocity and the radius of a star's orbit around a galaxy, you can calculate its orbital period. You followed this procedure in the previous chapter to estimate the mass of the Milky Way Galaxy. The circumference of the orbit (2π times the radius) divided by the orbital velocity equals the orbital period. So knowing the velocity and size of an orbit tells you the orbital period, and from that you can find the mass. That is why the rotation curve of a galaxy is so important; it contains all the information you need to find the mass of the galaxy, and the method is known as the **rotation curve method**. It is the most accurate way to find the mass, but it works only for the nearer galaxies, whose rotation curves can be observed. More distant galaxies appear so small astronomers cannot measure the radial velocity at different points across the galaxy.

You should note one warning about masses found from rotation curves. Recent studies of our own galaxy and others show that the outer parts of the rotation curve do not decline to lower velocities as you would expect if most of the mass lies in the inner part of the galaxy. As in the case of the rotation curve of the Milky Way Galaxy (see Figure 15-11), this indicates that the galaxies contain large amounts of mass outside this radius, perhaps in extended galactic coronae. Because the rotation curve method can be applied only to nearby galaxies and because it cannot determine the masses of galactic coronae, astronomers have looked at another way to find the masses of galaxies.

The **cluster method** of finding the masses of galaxies depends on the motions of galaxies within a cluster. If you measured the radial velocities of many individual galaxies in a cluster, you would find that some velocities are larger than others. You could ask how massive a cluster of that size must be to hold itself together, given the range of velocities in the cluster. That is the same as asking how massive the cluster must be to have an escape velocity larger than the velocity of the fastest galaxy. Solving this problem would tell you the mass of the entire cluster. Dividing the total mass of the cluster by the number of galaxies in the cluster yields the average mass of the galaxies. This method



■ **Figure 16-7**

(a) In the upper panel's artwork representation, an astronomer has placed the image of the galaxy over a narrow slit so that light from the galaxy can enter the spectrograph and produce a spectrum. A very short segment of the spectrum shows an emission line redshifted on the receding side of the rotating galaxy and blueshifted on the approaching side. Converting those Doppler shifts into velocities, the astronomer can plot the galaxy's rotation curve (right). (b) Real data are shown in the lower panel. Galaxy NGC 2998 is shown over the spectrograph slit, and the segment of the spectrum includes three emission lines. (Courtesy Vera Rubin)

contains the built-in assumption that the cluster is not flying apart. If it is, your result is too large. Because it seems likely that most clusters are held together by their own gravity, the method is probably valid.

A related way of measuring a galaxy's mass is called the **velocity dispersion method**. It is really a version of the cluster method. Instead of observing the motions of galaxies in a cluster, you could observe the motions of matter within a galaxy. In the spectra of some galaxies, broad spectral lines indicate that stars and gas are moving at high velocities. If you assume the galaxy is bound by its own gravity, you can ask how massive it must be to

hold this moving matter within the galaxy. This method, like the one before, assumes that the system is not coming apart.

Measuring the masses of galaxies reveals two things. First, the range of masses is wide—from 1 million times smaller than the Milky Way Galaxy to 50 times larger (■ Table 16-1). And second, galaxies contain dark matter spread through extended galactic coronae, just as does our Milky Way Galaxy.

One last region remains to be explored. What lies in the centers of galaxies? Our Milky Way Galaxy contains a 4 million-solar-mass black hole at its center. Do all galaxies contain similar objects?

■ **Table 16-1 | The Properties of Galaxies***

	Elliptical	Spiral	Irregular
Mass	0.0001–50	0.005–2	0.0005–0.15
Diameter	0.01–5	0.2–1.5	0.05–0.25
Luminosity	0.00005–5	0.005–10	0.00005–0.1

*In units of the mass, diameter, and luminosity of the Milky Way Galaxy

Supermassive Black Holes in Galaxies

Rotation curves show the motions of the outer parts of a galaxy, but it is also possible to detect the Doppler shifts of stars orbiting very close to the centers. Although these motions are not usually shown on rotation curves, they reveal something astonishing.

Measurements show that the stars near the centers of most galaxies are orbiting very rapidly. To hold stars in such small, short-period orbits, the centers of galaxies must contain millions or even billions of solar masses in a very small region. The evidence shows that the nuclei of many galaxies contain supermassive black holes. The Milky Way contains a supermassive black hole at its center (see Chapter 15), and evidently that is typical of galaxies.

Such a supermassive black hole cannot be the remains of a dead star. That would amount to only a few solar masses. Rather, a supermassive black hole either formed as the galaxy formed or accumulated mass over billions of years as matter sank into the center of the galaxy. Measurements show that the mass of a supermassive black hole is related to the mass of the central bulge. A galaxy with a large central bulge has a supermassive black hole whose mass is greater than the black hole in a galaxy with a small central bulge. Rare galaxies lacking central bulges usually also lack supermassive black holes (■ Figure 16-8). This suggests that the supermassive black holes formed long ago as the galaxies formed. Of course, matter has continued to drain into the black holes, but they do not appear to have grown dramatically since they formed.

A billion-solar-mass black hole sounds like a lot of mass, but note that it is roughly 1 percent of the mass of a galaxy. The 4-million-solar-mass black hole at the center of the Milky Way Galaxy contains only one-thousandth of 1 percent of the mass of our galaxy. In the next chapter you will discover that these supermassive black holes can produce titanic eruptions, but they still represent only a small fraction of the mass of a galaxy.

Dark Matter in Galaxies

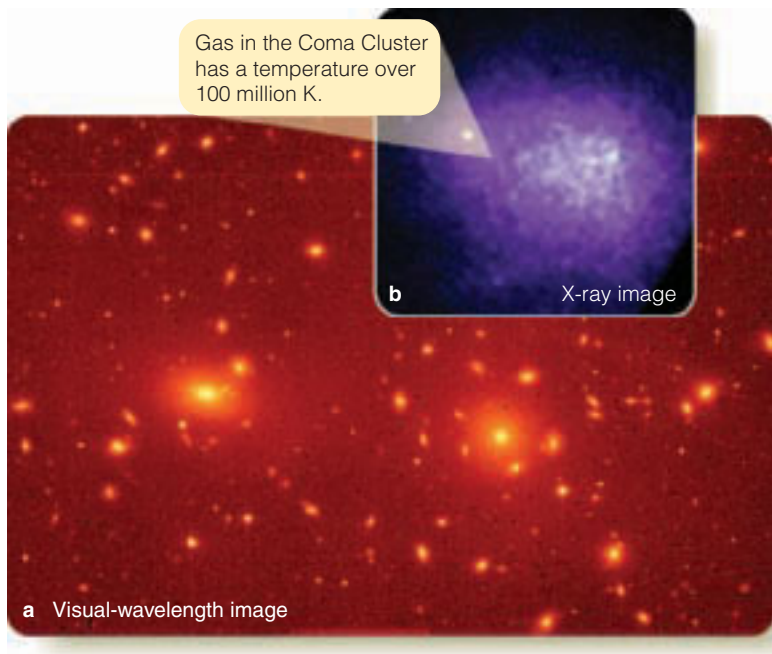
Given the size and luminosity of a galaxy, astronomers can make a rough guess as to the amount of matter it should contain. They know how much light stars produce, and they know about how much matter there is between the stars, so it is quite possible to estimate very roughly the mass of a galaxy from its luminosity. But when astronomers compare their estimates with measured masses of galaxies, they find that the measured masses are 10 times larger than the masses that can be seen. This must mean that nearly all galaxies contain dark matter. Theorists conclude that dark matter must be made up of some as yet undiscovered subatomic particles that do not interact with normal matter, with each other, or with light. Dark matter is detectable only through its gravitational field.

X-ray observations reveal more evidence of dark matter. X-ray images of galaxy clusters show that many of them are filled with very hot, low-density gas. The amount of gas present is much too small to account for the dark matter. Rather, the gas is



■ **Figure 16-8**

The galaxy M33 is near our Milky Way Galaxy, and it can be studied in detail. The velocities at the center of the galaxy are low, showing that it does not contain a supermassive black hole at its center. It also lacks a central bulge, and that confirms the observation that, with few exceptions, the mass of a supermassive black hole is related to the size of a galaxy's central bulge. (Bill Schoening/AURA/NOAO/NSF)



■ **Figure 16-9**

(a) The Coma cluster of galaxies contains at least 1000 galaxies and is especially rich in E and S0 galaxies. Two giant galaxies lie near its center. Only the central area of the cluster is shown in this image. If the cluster were visible in the sky, it would span eight times the diameter of the full moon. (Gregory Bothun, University of Oregon) (b) In false colors, this X-ray image of the Coma cluster shows it filled and surrounded by hot gas. Note that the two brightest galaxies are visible in the X-ray image. (NASA/CXC/SAO/A. Vikhlinin et al.)

important because it is very hot and its rapidly moving atoms have not leaked away. Evidently the gas is held in the cluster by a strong gravitational field. To have a high enough escape velocity to hold the hot gas, the cluster must contain much more matter than what astronomers can observe directly. The detectable galaxies in the Coma cluster, for instance, amount to only a small fraction of the total mass of the cluster (■ Figure 16-9).

Dark matter is a significant issue. Observations of galaxies and clusters of galaxies show that approximately 90 percent of the matter in the universe is dark matter. The universe you see—the kind of matter that you and the stars are made of—has been compared to the foam on an invisible ocean.

Gravitational Lensing and Dark Matter

When you solve a math problem and get an answer that doesn't seem right, you check your work for a mistake. Astronomers using Newton's laws (for example, calculations of orbital velocity and escape velocity) to measure the mass of galaxies find evidence of large amounts of dark matter, so they look for ways to check their work. Fortunately, there is another way to detect dark matter that does not depend on Newton's laws. Astronomers can follow a light beam.

Albert Einstein described gravity as a curvature of space-time (see Chapter 5). The presence of mass actually distorts space-time, and that is what you feel as gravity. He predicted that a light beam traveling through a gravitational field would be deflected by the curvature of space-time much as a golf ball is deflected as it rolls over a curved putting green. That effect has been observed and is a strong confirmation that Einstein's theories are correct.

Gravitational lensing occurs when light from a distant object passes a nearby massive object and is deflected by the gravitational field. The gravitational field of the nearby object is actually a region of curved space-time that acts as a lens to deflect the passing light. Astronomers can use gravitational lensing to detect dark matter when light from very distant galaxies passes through a cluster of galaxies on its way to Earth and is deflected by the strong curvature. The distortion can produce multiple images of the distant galaxies and distort them into arcs. The amount of the distortion depends on the mass of the

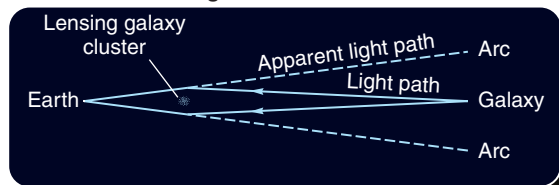
cluster of galaxies (■ Figure 16-10a). Observations of gravitational lensing made with very large telescopes reveal that clusters of galaxies contain far more matter than what can be seen. That is, they contain large amounts of dark matter. This confirmation of the existence of dark matter is independent of Newton's laws and gives astronomers great confidence that dark matter is real.

Dark matter is difficult to detect, and it is even harder to explain. The halos of galaxies contain faint objects such as white dwarfs, red dwarfs, and brown dwarfs, but not nearly enough to be the dark matter. It can't be black holes and neutron stars, because astronomers don't find the X-rays those objects would emit. Remember, there must be roughly 10 times more dark matter than visible matter, and such a huge number of black holes and neutron stars would produce X-rays that should be easy to detect.

Dark matter is so peculiar a few scientists have speculated that it isn't real, and that some quirk of gravity makes it seem that there is dark matter in the universe. Observations contradict this idea. Visual observations have identified two clusters of galaxies that passed through each other about 100 million years ago. X-ray observations show that the hot gas in the clusters collided and was swept out of the clusters by the collision, but gravitational lensing measurements show that the clusters still contain dark matter. As predicted by theory, the dark matter did not collide as the gas did and is still in the clusters. You can see the gas as the pink areas in Figure 16-10b and the locations of the dark matter as the purple areas. This shows that dark matter really exists and is not a quirk of gravitational theory.

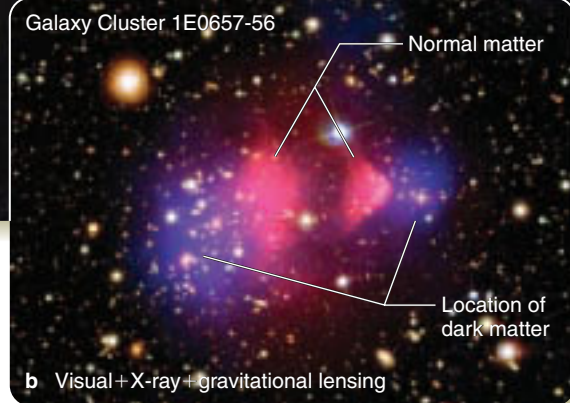
Dark matter remains one of the fundamental unresolved problems of modern astronomy. You will learn more about this problem in Chapter 18 when you try to understand how dark matter affects the nature of the universe, its past, and its future.

Gravitational lensing



Galaxy Cluster 0024+1654

a Visual-wavelength image



b Visual+X-ray+gravitational lensing

Figure 16-10

(a) The gravitational lens effect is visible in galaxy cluster CL 0024+1654 as its mass bends the light of a much more distant galaxy. This reveals that the galaxy cluster must contain large amounts of dark matter. (W. N. Colley and E. Turner, Princeton, and J. A. Tyson, Bell Labs, and NASA) (b) When two galaxy clusters passed through each other, normal matter (pink) collided and was swept out of the clusters, but the dark matter (purple), detected by gravitational lensing, was not affected. (NASA/CXC/CfA/STScI/Magellan/ESO WFI)

SCIENTIFIC ARGUMENT

Why do you have to know the distance to a galaxy to find its mass?

A good scientific argument proceeds step by step in a chain of inference with no gaps. This is a good example. To find the mass of a galaxy, you need to know the size of the orbits and the orbital periods of stars at the galaxy's outer edge and then use Kepler's third law to find the mass inside the orbits. Measuring the orbital velocity of the stars as the galaxy rotates is easy if you can obtain a rotation curve from a spectrum. But you must also know the radii of the stars' orbits in meters or astronomical units. That is where the distance comes in. Once you know the distance to the galaxy, you can use the small-angle formula to convert the radius in arc seconds into a radius in parsecs, in AU, or in meters. If your measurement of the distance to the galaxy isn't accurate, you will get inaccurate radii for the orbits and will compute an inaccurate mass for the galaxy.

Many different measurements in astronomy depend on the calibration of the distance scale. Build a step-by-step argument to analyze the following problem. **What would happen to your measurements of the diameters and luminosities of the galaxies if astronomers discovered that the Cepheid variable stars were slightly more luminous than had been thought?**

16-3 The Evolution of Galaxies

YOUR GOAL IN THIS CHAPTER is to build a theory to explain the evolution of galaxies. In Chapter 15 you considered the origin of our own Milky Way Galaxy; presumably, other galaxies formed similarly. But why did some galaxies become spiral, some elliptical, and some irregular? An important clue to that mystery lies in the clustering of galaxies.

Clusters of Galaxies

Single, isolated galaxies are rare. Instead, most galaxies occur in clusters containing a few to a few thousand galaxies in volumes 1 to 10 Mpc across (■ Figure 16-11). Our Milky Way Galaxy is a member of a small cluster, and surveys have cataloged thousands of other clusters.

For purposes of this study, you can sort clusters of galaxies into rich clusters and poor clusters. **Rich clusters** contain a thousand or more galaxies, mostly ellipticals, scattered through a



Visual-wavelength image

Figure 16-11

The Hercules galaxy cluster is named after the constellation in which it is found. It is a small cluster containing roughly a hundred galaxies, both elliptical and spiral. It lies over 500 million light-years from our galaxy. (NOAO/AURA/NSF)

volume roughly 3 Mpc (10^7 ly) in diameter. Such a cluster is nearly always condensed; that is, the galaxies are more crowded near the cluster center. At their centers, such clusters often contain one or more giant elliptical galaxies.

The Virgo cluster is an example of a rich cluster. It contains over 2500 galaxies and is about 18 Mpc (59 million ly) from our galaxy. The Virgo cluster, like most rich clusters, is centrally condensed and contains the giant elliptical galaxy M87 at its center (page 334).

X-ray observations have found that many of these rich clusters are filled with a hot gas—an intracluster medium. Some of this gas has presumably been driven out of galaxies by supernovae explosions, but much of it appears to be left over from the formation of galaxies.

Poor clusters contain fewer than a thousand (and often only a few) galaxies spread through a region that can be as large as a rich cluster. That means the galaxies are more widely separated.

Our Milky Way Galaxy is a member of a poor cluster known by the unimaginative name of the Local Group (Figure 16-12a). The total number of galaxies in the Local Group is uncertain, but it probably contains about 40 galaxies scattered irregularly through a volume roughly 1 Mpc in diameter. Of the brighter galaxies, 15 are elliptical, 4 are spiral, and 13 are irregular.

The total number of galaxies in the Local Group is uncertain because some galaxies lie in the plane of the Milky Way Galaxy and are difficult to detect. For example, a small galaxy

known as the Sagittarius Dwarf has been found on the far side of our own galaxy, where it is almost totally hidden behind the star clouds of Sagittarius (Figure 16-12b). Even closer to the Milky Way Galaxy is the Canis Major Dwarf Galaxy (Figure 16-12c). This galaxy was found by mapping the distribution of red supergiants detected by the 2MASS infrared survey. There are certainly other small galaxies in our Local Group that have not been detected yet.

Poor galaxy clusters tend not to be centrally condensed; rather, they tend to have subclusters with smaller galaxies crowded around larger galaxies. The Local Group illustrates this subclustering. The two largest galaxies, the Milky Way Galaxy and the Andromeda Galaxy, are the centers of two subclusters. The Milky Way Galaxy is accompanied by the Magellanic Clouds and at least seven other dwarf galaxies. The Andromeda Galaxy is attended by more dwarf elliptical galaxies and a small spiral, M33 (look again at Figure 16-8). The Andromeda Galaxy and our Milky Way Galaxy, with their retinues of smaller galaxies, are known to be moving toward each other and will almost certainly collide within a few billion years.

From all of this, you can draw an important conclusion: Galaxies do not live in isolation. They are usually found in clusters, often interact with nearby companions, and may even collide with each other. That leads to a critical clue hidden in the clusters of galaxies—the relative abundance of the different types of galaxies.

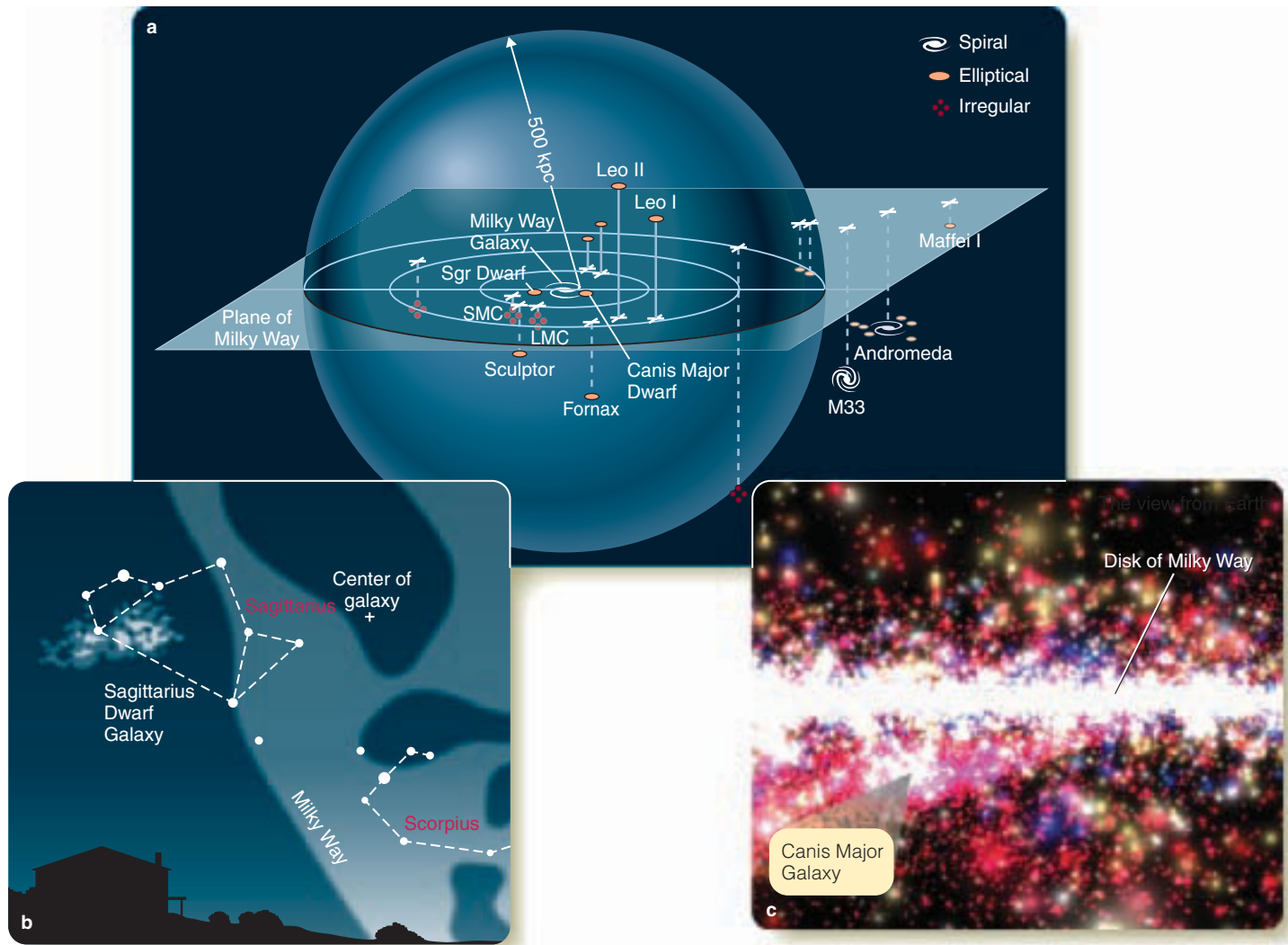


Figure 16-12

(a) The Local Group. Our galaxy is located at the center of this diagram. The vertical lines giving distances from the plane of the Milky Way are solid above the plane and dashed below. (b) The Sagittarius Dwarf Galaxy (Sgr Dwarf) lies on the other side of our galaxy. If you could see it in the sky, its minor axis would be 17 times wider than the full moon. (c) The Canis Major Dwarf Galaxy, shown in this simulation, is even closer to the Milky Way Galaxy. It is the remains of a small galaxy that is being pulled apart by our galaxy and is hidden behind the stars of the constellation Canis Major. (Nicolas Martin and Rodrigo Ibata, Strasbourg Observatory)

In general, rich clusters tend to contain 80 to 90 percent E and S0 galaxies and a few spirals. In other words, galaxies that are crowded together tend to be E or S0 rather than spirals. Poor clusters contain a larger percentage of spirals. Among the rare isolated galaxies that are not in clusters, 80 to 90 percent are spirals. Somehow the environment around a galaxy helps determine its type.

Astronomers suspect that collisions between galaxies are an important process. In a rich cluster, the galaxies are much closer

together, and they must collide with each other more often than galaxies in a poor cluster. Could such collisions explain the excess of elliptical galaxies in the rich clusters? Astronomers have discovered that galaxy smashups are both important and entertaining.

Colliding Galaxies

Galaxies should collide fairly often. The average separation between galaxies is only about 20 times their diameter. Like two blindfolded elephants blundering about under a circus tent, galaxies should bump into each other once in a while. Stars, on the other hand, almost never collide. In the region of the galaxy near the sun, the average separation between stars is about 10^7 times their diameters. Consequently, a collision between two stars inside a galaxy is about as likely as collision between two gnats flitting about in a football stadium.

Read **Interacting Galaxies** on pages 348–349 and notice four important points and three new terms:

- 1 Interacting galaxies can distort each other with tides producing *tidal tails* and shells of stars. They may even trigger the formation of spiral arms. In fact, large galaxies can even absorb smaller galaxies, a process called *galactic cannibalism*.
- 2 Interactions between galaxies can trigger rapid star formation.
- 3 Evidence left inside galaxies in the form of motions and multiple nuclei reveals that they have suffered past interactions and mergers.
- 4 Finally, the beautiful *ring galaxies* are understood to be bull's-eyes left behind by high-speed collisions.

Evidence of galaxy mergers is all around you. Our Milky Way Galaxy is a cannibal galaxy snacking on the nearby Magellanic Clouds. Furthermore, our galaxy's tides are pulling the Sagittarius Dwarf Galaxy apart, and the Canis Major Dwarf Galaxy has been almost completely digested as tides have pulled stars away to form great streamers wrapped around the Milky Way Galaxy (■ Figure 16-13). Our galaxy has almost certainly dined on other small galaxies.

Infrared observations of the nearby Andromeda Galaxy show that it contains two dusty rings, a small inner ring and a larger outer ring. These appear to have been produced when the

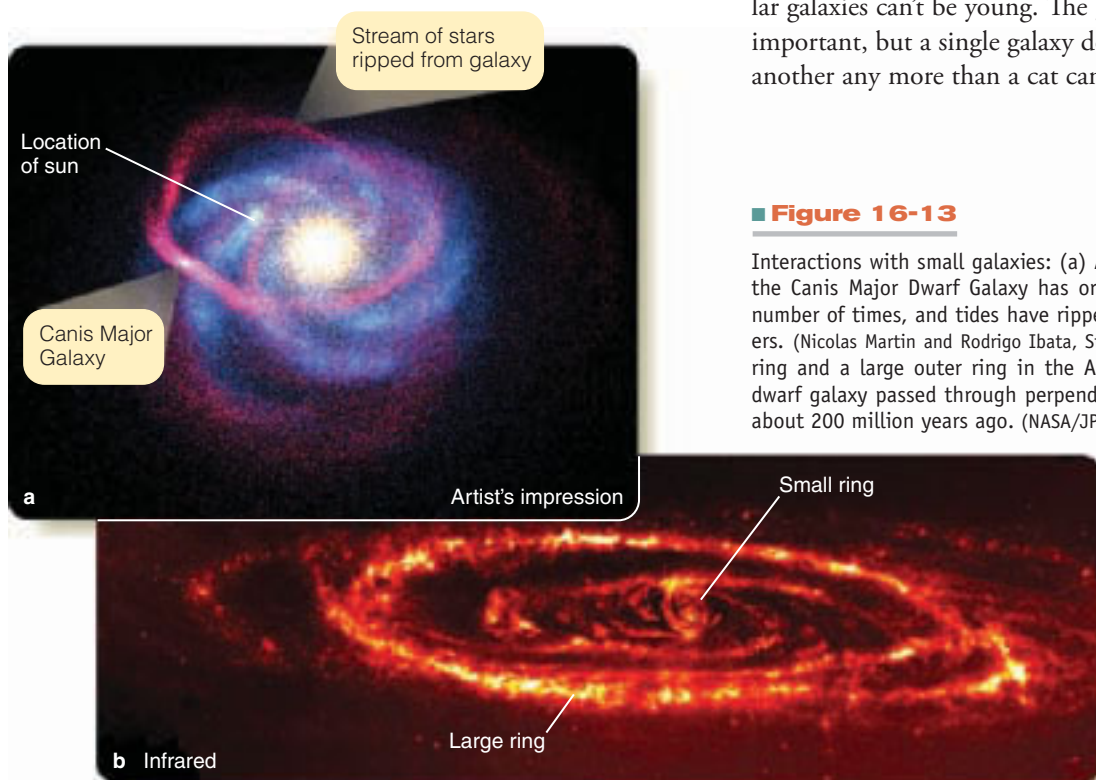
dwarf elliptical galaxy M32 plunged through the galaxy nearly perpendicular to the disk. You can see the rings in Figure 16-13b, and you can locate M32 below and to the left of the nucleus of the Andromeda Galaxy in Figure 15-1

You have seen the evidence that collisions and mergers between galaxies are common and can produce dramatic changes in the structure of the galaxies; now you are ready to evaluate a hypothesis that may explain how galaxies form and evolve.

The Origin and Evolution of Galaxies

The test of any scientific understanding is whether you can put all the evidence and theory together to tell the history of the objects studied. Can you describe the origin and evolution of the galaxies? Just a few decades ago, it would have been impossible, but the evidence from space telescopes and new-generation telescopes on Earth, combined with advances in computer modeling and theory, allows astronomers to outline the story of the galaxies.

Before you begin, you should eliminate a few older ideas immediately. It is so easy to imagine that galaxies normally evolve from one type to another that you could call that a **Common Misconception**. But an elliptical galaxy cannot become a spiral galaxy or an irregular galaxy because ellipticals contain almost no gas and dust from which to make new stars. That means elliptical galaxies can't be young galaxies. But you can also argue that spiral and irregular galaxies cannot evolve into elliptical galaxies because spiral and irregular galaxies contain old stars as well as young stars. The old stars tell you that spiral and irregular galaxies can't be young. The galaxy classes tell you something important, but a single galaxy does not change from one class to another any more than a cat can change into a dog.



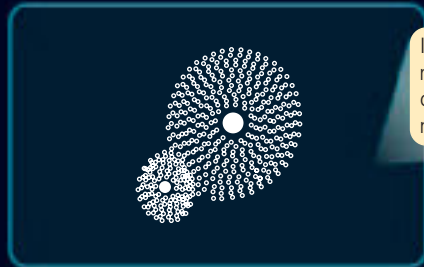
■ **Figure 16-13**

Interactions with small galaxies: (a) As shown in this mathematical model, the Canis Major Dwarf Galaxy has orbited around the Milky Way Galaxy a number of times, and tides have ripped stars and gas away to form streamers. (Nicolas Martin and Rodrigo Ibata, Strasbourg Observatory) (b) A small inner ring and a large outer ring in the Andromeda Galaxy are evidence that a dwarf galaxy passed through perpendicular to the disk of the larger galaxy about 200 million years ago. (NASA/JPL D. Block)

Interacting Galaxies

1 When two galaxies collide, they can pass through each other without stars colliding because the stars are so far apart relative to their sizes. Gas clouds and magnetic fields do collide, but the biggest effects may be tidal. Even when two galaxies just pass near each other, tides can cause dramatic effects, such as long streamers called **tidal tails**. In some cases, two galaxies can merge and form a single galaxy.

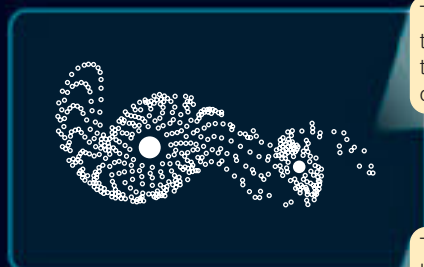
Galaxy interactions can stimulate the formation of spiral arms



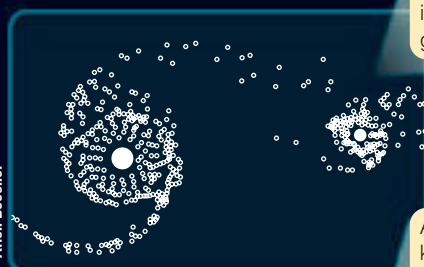
In this computer model, two uniform disk galaxies pass near each other.



The small galaxy passes behind the larger galaxy so they do not actually collide.



Tidal forces deform the galaxies and trigger the formation of spiral arms.



The upper arm of the large galaxy passes in front of the small galaxy.



A photo of the well-known Whirlpool Galaxy resembles the computer model.

Allen Beechell

NOAO

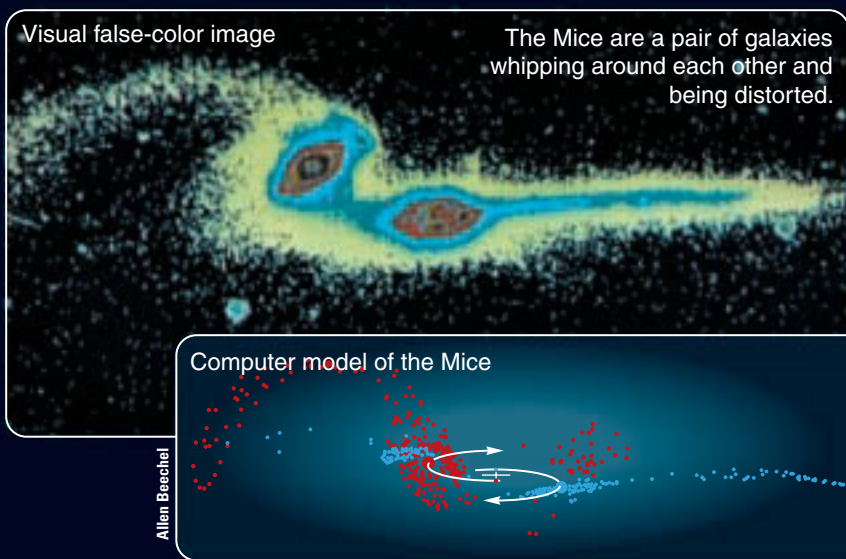
Tidal Distortion

Small galaxy passing near a massive galaxy.



Gravity of a second galaxy represented as a single massive object

1a When a galaxy swings past a massive object such as another galaxy, tides are severe. Stars near the massive object try to move in smaller, faster orbits while stars farther from the massive object follow larger, slower orbits. Such tides can distort a galaxy or even rip it apart.



Visual false-color image

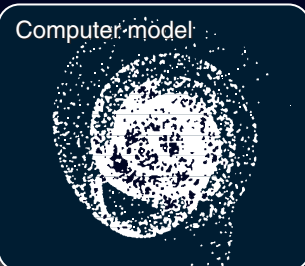
The Mice are a pair of galaxies whipping around each other and being distorted.

Computer model of the Mice

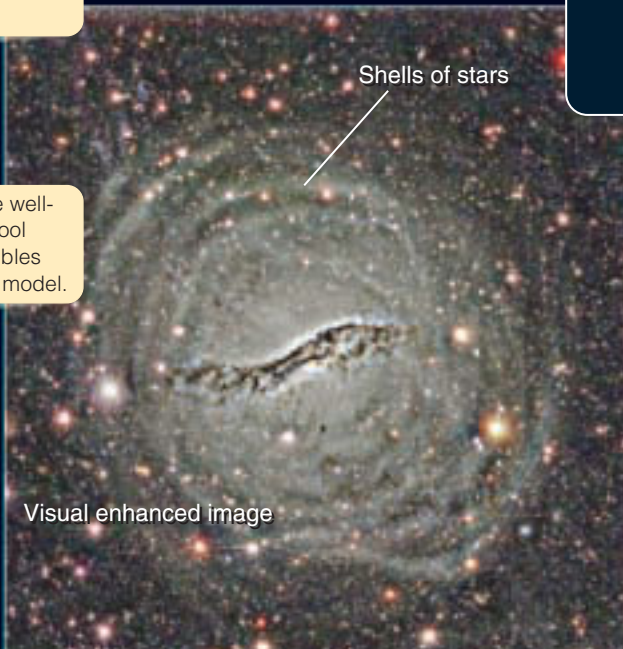
Allen Beechell

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1b The merger of galaxies is called **galactic cannibalism**. Models show that merging galaxies spiral around their common center of mass while tides rip stars away and form shells.



Francois Schweizer and Alar Toomre



Shells of stars

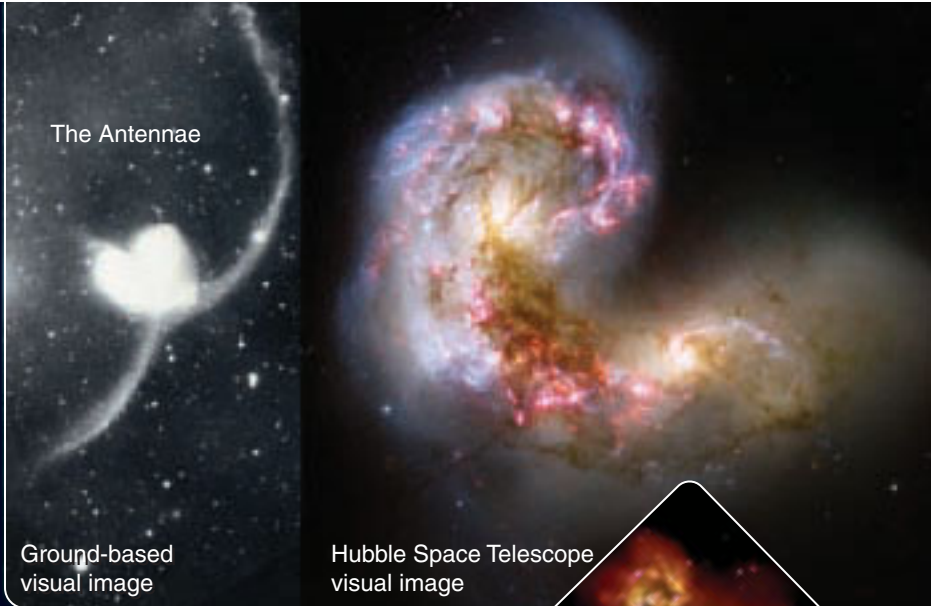
NOAO

Visual enhanced image

Such shells have been found around elliptical galaxies such as NGC 5128. It is peculiar in many ways and even has a belt of dusty gas. The shells revealed in this enhanced image are evidence that the giant galaxy has cannibalized at least one smaller galaxy. The giant galaxy itself may be the result of the merger of two large galaxies.

2 The collision of two galaxies can trigger firestorms of star formation as gas clouds are compressed. Galaxies NGC 4038 and 4039 have been known for years as the Antennae because the long tails visible in Earth-based photos resemble the antennae of an insect. Hubble Space Telescope images reveal that the two galaxies are blazing with star formation. Roughly a thousand massive star clusters have been born.

Spectra show that the Antennae galaxies are 10 to 20 times richer in elements such as magnesium and silicon than the Milky Way. Such metals are produced by massive stars and spread by supernova explosions.



Brad Whitmore, STScI/NASA

3 Evidence of past galaxy mergers shows up in the motions inside some galaxies. NGC 7251 is a highly distorted galaxy with tidal tails in this ground-based image.

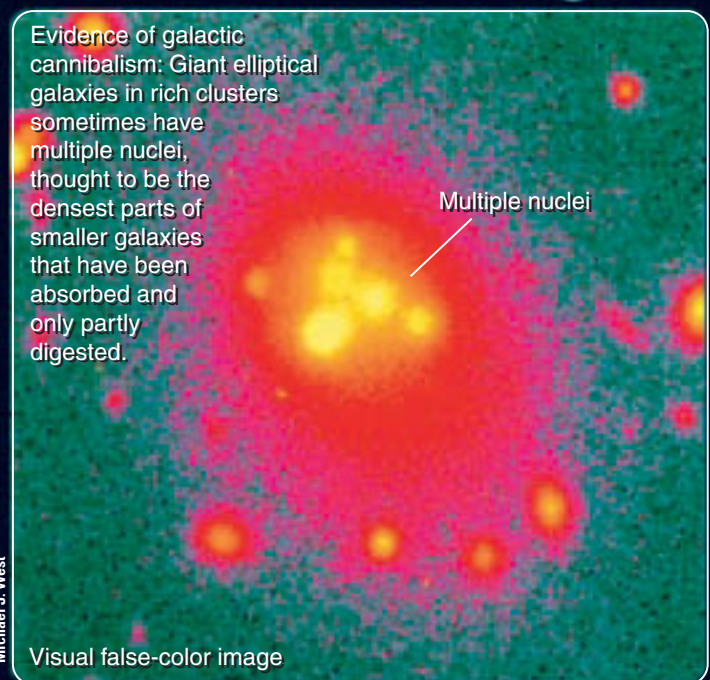


Francois Schweizer, Carnegie Inst. of Washington, Brad Whitmore, STScI

This Hubble Space Telescope image of the core of the galaxy reveals a small spiral spinning backward in the heart of the larger galaxy.



This rotation suggests that NGC 7251 is the remains of two oppositely rotating galaxies that merged about a billion years ago.

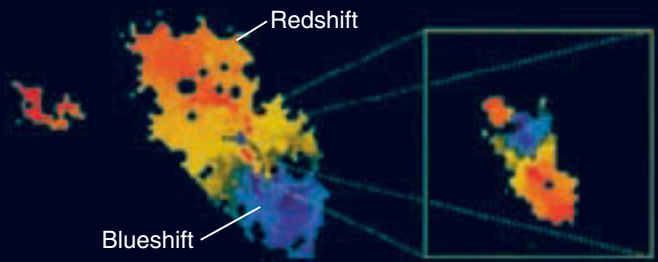


Evidence of galactic cannibalism: Giant elliptical galaxies in rich clusters sometimes have multiple nuclei, thought to be the densest parts of smaller galaxies that have been absorbed and only partly digested.

Michael J. West

3a Radio evidence of past mergers: Doppler shifts reveal the rotation of the spiral galaxy M64. The upper part of the galaxy has a redshift and is moving away from Earth, and the bottom part of the galaxy has a blueshift and is approaching. A radio map of the core of the galaxy reveals that it is rotating backward. This suggests a merger long ago between two galaxies that rotate in opposite directions.

Rotation of galaxy M64



Robin Braun, NRAO/AUI/NSF

4 The Cartwheel galaxy below was once a normal galaxy but is now a **ring galaxy**. One of its smaller companions has plunged through at high speed almost perpendicular at the Cartwheel's disk. That has triggered a wave of star formation, and the more massive stars have exploded leaving behind black holes and neutron stars. Some of those are in X-ray binaries, and that makes the outer ring bright in X-rays.

Purple = X-ray
Blue = UV
Green = Visible
Red = Infrared



Compositer: NASA/JPL/Caltech/P. Appleton et al. X-ray: NASA/CXC/A. Wolter & G. Trinchieri

Another old idea held that a galaxy that formed from a rapidly rotating cloud of gas would have lots of angular momentum and would contract slowly to form a disk-shaped spiral galaxy. A cloud of gas that rotated less rapidly would contract faster, form stars quickly, use up all of its gas and dust, and become an elliptical galaxy. This reflects the original hypothesis that galaxies formed from the top down—from a single large cloud of gas. That idea is mentioned in the previous chapter as the “monolithic collapse hypothesis.” Modern evidence clearly shows that galaxies form partly from the bottom up—from the gradual accumulation of smaller clouds of gas and stars and, in some cases, entire galaxies. Collisions and mergers dominate the history of the galaxies.

Ellipticals appear especially to be the product of galaxy collisions and mergers. They are devoid of gas and dust because it was used up in the rapid star formation triggered by the interaction. In fact, astronomers see many **starburst galaxies** that are very luminous in the infrared because a recent collision has triggered a burst of star formation that is heating the dust (■ Figure 16-14), which reradiates the energy in the infrared. Some of these galaxies are a hundred times more luminous than our Milky Way Galaxy but so deeply shrouded in dust that they are very dim at visible wavelengths. Such **ultraluminous infrared galaxies (ULIRGs)** show evidence of tidal tails and are probably the result of the merger of three or more galaxies that

triggered firestorms of star formation and generated tremendous clouds of dust. The Antennae Galaxies (page 349) contain over 15 billion solar masses of hydrogen gas and will become a starburst galaxy as the ongoing merger continues to trigger rapid star formation. As these galaxies use up the last of their gas and dust making stars, they will probably become normal elliptical galaxies or merge to form a single elliptical.

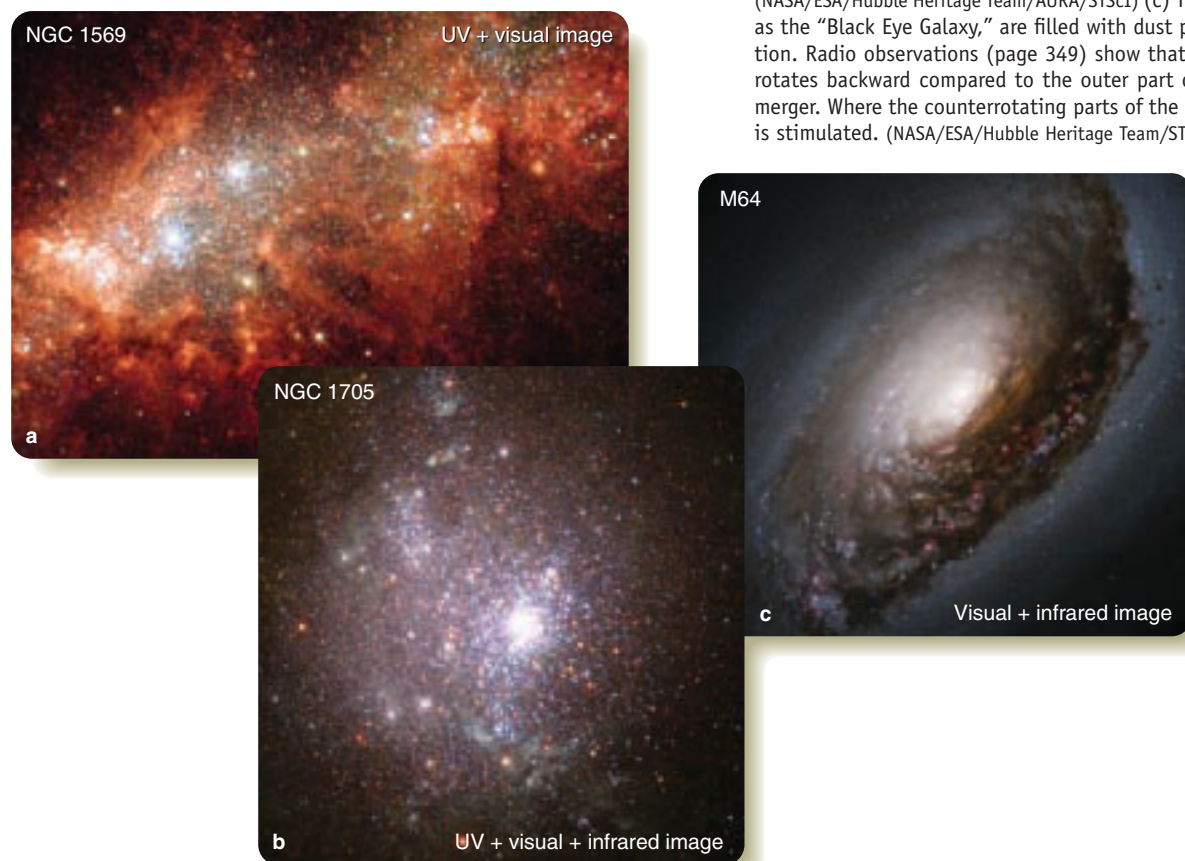
Another process can help clear the gas and dust out of elliptical galaxies. Supernovae in a starburst galaxy can blow away the remaining gas and dust, and a burst of rapid star formation produces lots of supernova explosions.

In this way, a few collisions and mergers could leave a galaxy with no gas and dust from which to make new stars and could scramble the orbits of the remaining stars to produce an elliptical shape. Astronomers now suspect that most elliptical galaxies are formed by the merger of at least two or three galaxies of comparable size.

In contrast, spirals have never suffered major collisions. Their thin disks are delicate and would be destroyed by the tidal

■ Figure 16-14

Rapid star formation: (a) NGC 1569 is a starburst galaxy filled with clouds of young stars and supernovae. At least some starbursts are triggered by interactions between galaxies. (ESA/NASA/P. Anders) (b) The dwarf irregular galaxy NGC 1705 began a burst of star formation about 25 million years ago. (NASA/ESA/Hubble Heritage Team/AURA/STScI) (c) The inner parts of M64, known as the “Black Eye Galaxy,” are filled with dust produced by rapid star formation. Radio observations (page 349) show that the inner part of the galaxy rotates backward compared to the outer part of the galaxy, a product of a merger. Where the counterrotating parts of the galaxy collide, star formation is stimulated. (NASA/ESA/Hubble Heritage Team/STScI/AURA)



forces generated during a collision with a massive galaxy. Also, they retain plenty of gas and dust and continue making stars, so they have never experienced a major starburst triggered by a merger.

Of course, spiral galaxies can safely cannibalize smaller galaxies with no ill effects. The small galaxies do not generate strong tides to distort a full-sized galaxy. You have seen plenty of evidence of cannibalism in our own galaxy, and some astronomers suspect that much of the halo consists of the remains of cannibalized galaxies. Evidently our Milky Way Galaxy has not collided with a galaxy of size comparable to itself, so far. Such a collision would trigger rapid star formation, use up gas and dust, scramble the orbits of stars, and destroy the thin disk. However, other evidence indicates that our galaxy will merge with the approaching Andromeda Galaxy, and the final result probably will be a large elliptical galaxy.

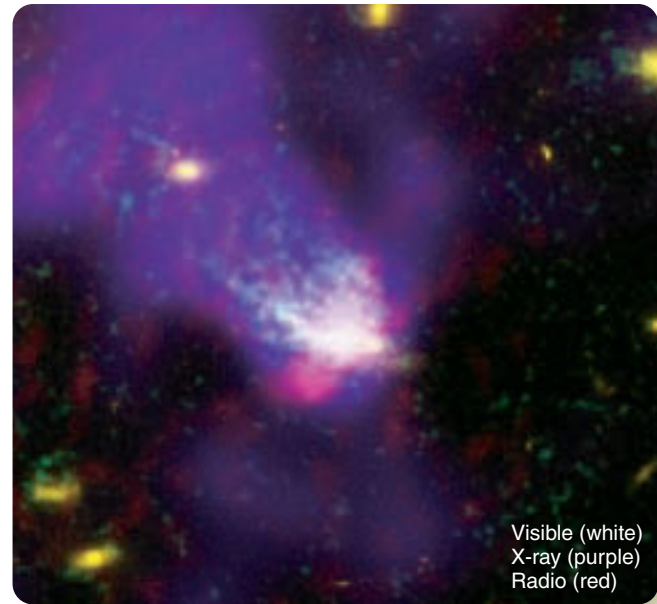
Just as people do, spiral galaxies may need some interaction to fully develop. Only one in 10,000 galaxies is isolated from its neighbors; and, although most of these are disk galaxies, many are flocculent without a strong two-armed spiral pattern. Some isolated galaxies are rich in gas and dust but have little star formation. All of this suggests, as was discussed in the previous chapter, that continuous gentle gravitational interactions with neighboring galaxies is necessary to stimulate spiral structure and star formation.

Earlier, the Virgo cluster was cited as a rich cluster, so you may find it surprising to learn that it contains lots of spiral galaxies. Rich clusters are supposed to contain few spirals. Astronomers hypothesize that the cluster is so massive that the galaxies orbit the center of mass of the cluster at such high speeds that they rush past each other too quickly to interact strongly. The galaxies are whittled down a bit, but many are still disk galaxies with spiral patterns.

Barred spiral galaxies may also be the products of tidal interactions. Mathematical models show that bars are not stable and eventually dissipate. Tidal interactions with other galaxies may regenerate the bars. Well over half of all spiral galaxies have bars, suggesting that these tidal interactions are common.

Other processes can alter galaxies. The S0 galaxies retain a disk shape but lack gas and dust. Although they could have lost gas and dust during starburst episodes, they may also have lost it as they orbited through the gas in their respective clusters. A galaxy moving rapidly through the thin gas filling a cluster would encounter a tremendous wind that could blow the galaxy's gas and dust away. In this way, a disk-shaped spiral galaxy could be reduced to an S0 galaxy. For example, X-ray observations show that the Coma cluster contains thin, hot gas between the galaxies (Figure 16-9), and astronomers have located, in a similar cluster, a galaxy in the act of plunging through such gas and being stripped of its gas and dust (■ Figure 16-15).

Small galaxies may be produced in a number of ways. The dwarf ellipticals are too small to be produced by mergers, but



■ **Figure 16-15**

The distorted galaxy C153 is orbiting through the thin gas in its home cluster of galaxies at 2000 km/s (4.5 million mph). At that speed, it feels a tremendous wind stripping gas out of the galaxy in a trail 200,000 ly long. Such galaxies could quickly lose almost all of their gas and dust. (NASA, W. Keel, F. Owen, M. Ledlow, and D. Wang)

they could be fragments of galaxies ripped free during interactions. Another possibility is that the dwarf ellipticals are small galaxies that have plunged through the gas in a cluster of galaxies and lost their gas and dust. In contrast, the irregular galaxies may be small fragments splashed from larger galaxies during collisions but retaining enough gas and dust to continue forming stars.

Other factors must influence the evolution of galaxies. The hot gas in galaxy clusters warns that galaxies rarely form in isolation. Cooler gas clouds may fall into galaxies and add material for star formation. These processes are just beginning to be understood.

A good theory helps you understand how nature works, and astronomers are beginning to understand the exciting and complex story of the galaxies. Nevertheless, it is already clear that galaxy evolution bears some resemblance to a pie-throwing contest.

The Farthest Galaxies

Observations made with the largest and most sophisticated telescopes are taking astronomers back to the age of galaxy formation. At great distances the look-back time is so great that the universe can be seen as it was soon after the galaxies began to form. There were more spirals then and fewer ellipticals. On the whole, galaxies long ago were more compact and more irregular than they are now. The observations also show that galaxies were closer together long ago; about a third of all distant galaxies are

in close pairs, but only 7 percent of nearby galaxies are in pairs. The observational evidence clearly supports the hypothesis that galaxies have evolved by merger.

At great distances, astronomers see tremendous numbers of small, blue, irregularly shaped galaxies that have been called blue dwarfs. The blue color indicates that they are rapidly forming stars, but the role of these blue dwarfs in the formation of galaxies is not clear. Blue dwarf galaxies are not found at small look-back times, so they no longer exist in the present universe. They may be clouds of gas and stars that were absorbed long ago in the

formation of larger galaxies, or they may have used up their gas and dust and faded into obscurity.

At the limits of the largest telescopes, astronomers see faint red galaxies (■ Figure 16-16). They look red from Earth because of their great redshifts. The floods of ultraviolet light emitted by these star-forming galaxies have been shifted into the far-red part of the spectrum. Their look-back times are so great that they appear as they were when the universe was only a billion years old. These galaxies seem to be among the first to begin shining after the beginning of the universe, a story told in Chapter 18.

SCIENTIFIC ARGUMENT

How did elliptical galaxies get that way?

Telling the story of a natural object is a goal that lies at the heart of science, and many scientific arguments tell such tales. A growing body of evidence suggests that elliptical galaxies have been subject to collisions in their past and that spiral galaxies have not. During collisions, a galaxy can be driven to use up its gas and dust in a burst of star formation, and the resulting supernova explosions can help drive gas and dust out of the galaxy. This explains why elliptical galaxies now contain little star-making material. The beautiful disk typical of spiral galaxies is very orderly, with all the stars following similar orbits. When galaxies collide, the stellar orbits get scrambled, and an orderly disk galaxy could be converted into a chaotic swarm of stars typical of elliptical galaxies. It seems likely that elliptical galaxies have had more complex histories than spiral galaxies have had.

When scientists create a scientific argument to tell the story of a natural object, they use evidence to make the story as true as it can be. Expand your argument. **What evidence can you cite to support the story in the preceding paragraph?**



Visual-wavelength image

■ Figure 16-16

Arrows point to three very distant red galaxies. The look-back time to these galaxies is so large that they appear as they were when the universe was only a billion years old. Such highly redshifted galaxies are believed to be among the first to form stars and begin shining after the beginning of the universe about 14 billion years ago. (NASA, H.-J. Yan, R. Windhorst and S. Cohen, Arizona State University)

What Are We? Small and Proud

Do you feel insignificant yet? You are riding a small planet orbiting a humdrum star that is just one of at least 100 billion stars in the Milky Way Galaxy, and you have just learned that there are at least a 100 billion galaxies visible with existing telescopes. When you look at galaxies you are looking across voids deeper than human imagination. You can express such distances with numbers and say a certain galaxy is 5 billion

light-years from Earth, but the distance is truly beyond human comprehension. Furthermore, looking at distant galaxies also leads you back in time. You see distant galaxies as they were billions years ago. The realm of the galaxies is deep space and deep time.

Some people say astronomy makes them feel humble; but, before you agree, consider that you can feel small without feeling

humble. Size is not necessarily the same thing as significance. We humans live out our little lives on our little planet, but our tiny brains are able to figure out some of the most profound mysteries of the universe. We are exploring deep space and deep time and coming to understand what galaxies are and how they evolve. Most of all, we humans are beginning to understand what we are. That's something to be proud of.

Study and Review

Summary

- ▶ Through 19th-century telescopes, galaxies looked like hazy **spiral nebulae (p. 332)**. Some astronomers said they were other star systems sometimes called **island universes (p. 332)**, but others said they were clouds of gas inside the Milky Way system. The controversy culminated in the **Shapley-Curtis debate (p. 332)** in 1920.
- ▶ A few years later, with the construction of larger telescopes, astronomers could identify stars, including Cepheid variable stars, in the spiral nebulae. That showed that the spiral nebulae were galaxies.
- ▶ Astronomers divide galaxies into three classes—**elliptical (p. 334)**, **spiral (p. 334)**, and **irregular (p. 335)**—with subclasses specifying the galaxy's shape.
- ▶ Elliptical galaxies contain little gas and dust and cannot make new stars. Consequently, they lack hot, blue stars and have a reddish tint.
- ▶ Spiral galaxies contain more gas and dust in their disks and support active star formation, especially along the spiral arms. Some of the newborn stars are massive, hot, and blue, and that gives the spiral arms a blue tint. About two-thirds of spirals, including our Milky Way Galaxy, are **barred spiral galaxies (p. 334)**.
- ▶ The halo and central bulge of a spiral galaxy usually lack gas and dust and contain little star formation. The halos and central bulges have a reddish tint because they lack hot, blue stars.
- ▶ Irregular galaxies have no obvious shape but contain gas and dust and support star formation.
- ▶ Galaxies are so distant astronomers measure their distances in **megaparsecs (Mpc) (p. 336)**—millions of parsecs.
- ▶ Astronomers find the distance to galaxies using **distance indicators (p. 337)**, sometimes called **standard candles (p. 337)**, objects of known luminosity. The most accurate distance indicators are the Cepheid variable stars. Globular clusters and type Ia supernovae explosions have also been calibrated as distance indicators.
- ▶ By calibrating additional distance indicators, astronomers have built a **distance scale (p. 338)**.
- ▶ When astronomers look at a distant galaxy, they see it as it was when it emitted the light now reaching Earth. The **look-back time (p. 338)** to distant galaxies can be a significant fraction of the age of the universe.
- ▶ According to the **Hubble law (p. 339)**, the apparent velocity of recession of a galaxy equals its distance times the **Hubble constant (p. 339)**. Astronomers can estimate the distance to a galaxy by observing its redshift, calculating its apparent velocity of recession, and then dividing by the Hubble constant.
- ▶ Once the distance to a galaxy is known, its diameter can be found from the small-angle formula and its luminosity from the magnitude-distance relation.
- ▶ Astronomers measure the masses of galaxies in two basic ways. The **rotation curve (p. 340)** of a galaxy shows the orbital motion of its stars, and astronomers can use the **rotation curve method (p. 340)** to find the galaxy's mass.
- ▶ The **cluster method (p. 340)** uses the velocities of the galaxies in a cluster to find the total mass of the cluster. The **velocity dispersion method (p. 341)** uses the velocities of the stars in a galaxy to find the total mass of the galaxy.
- ▶ Galaxies come in a wide range of sizes and masses. Some dwarf ellipticals and dwarf irregular galaxies are only a few percent of the size and luminosity of our galaxy, but some giant elliptical galaxies are five times larger than the Milky Way Galaxy.
- ▶ Stars near the centers of galaxies are following small orbits at high velocities, which suggests the presence of supermassive black holes in the centers of most galaxies.
- ▶ The mass of a galaxy's supermassive black hole is proportional to the mass of its central bulge. This shows that the supermassive black holes must have formed when the galaxy formed.
- ▶ Observations of individual galaxies show that galaxies contain 10 to 100 times more dark matter than visible matter.
- ▶ The hot gas held inside some clusters of galaxies and the **gravitational lensing (p. 343)** caused by the mass of galaxy clusters reveal that the clusters must be much more massive than can be accounted for by the visible matter—further evidence of dark matter.
- ▶ **Rich clusters (p. 344)** of galaxies contain thousands of galaxies with fewer spirals and more ellipticals. **Poor clusters (p. 345)** of galaxies contain few galaxies with a larger proportion of spirals. This is evidence that galaxies evolve by collisions and mergers.
- ▶ When galaxies collide, tides twist and distort their shapes and can produce **tidal tails (p. 348)**.
- ▶ Large galaxies can absorb smaller galaxies in what is called **galactic cannibalism (p. 348)**. There is clear evidence that our own Milky Way Galaxy is devouring some of the small galaxies that orbit nearby and that our galaxy has consumed other small galaxies in the past.
- ▶ Shells of stars, counterrotating parts of galaxies, streams of stars in the halos of galaxies, and multiple nuclei are evidence that galaxies can merge.
- ▶ **Ring galaxies (p. 349)** are produced by high-speed collisions in which a small galaxy plunges through a larger galaxy perpendicular to its disk.
- ▶ The compression of gas clouds can trigger rapid star formation, producing **starburst galaxies (p. 350)**. The rapid star formation can produce lots of dust, which is warmed by the stars to emit infrared radiation, making the galaxy an **ultraluminous infrared galaxy (ULIRG) (p. 350)**.
- ▶ The merger of two larger galaxies can scramble star orbits and drive bursts of star formation to use up gas and dust. Most large ellipticals have evidently been produced by past mergers.
- ▶ Spiral galaxies have thin, delicate disks and appear not to have suffered mergers with large galaxies.
- ▶ A galaxy moving through the gas in a cluster of galaxies can be stripped of its own gas and dust and may become an S0 galaxy.
- ▶ Rare isolated galaxies tend to be spirals and lack a bar or a strong two-armed spiral pattern, which suggests that gentle interactions with neighbors are needed to stimulate the formation of bars and spiral arms.
- ▶ At great distance and great look-back times, the largest telescopes reveal that galaxies were smaller, more irregular, and closer together. There were more spirals and fewer ellipticals long ago.
- ▶ At the largest distances, astronomers find small irregular clouds of stars that may be the original objects that fell together to begin forming galaxies when the universe was very young.

Review Questions

1. If a civilization lived on a planet in an E0 galaxy, do you think they would have a "Milky Way" band of starlight in their sky? Why or why not?
2. Why can't the evolution of galaxies go from elliptical to spiral? From spiral to elliptical?

- If all elliptical galaxies had three different diameters, you would never see an elliptical galaxy with a circular outline on a photograph. True or false? Explain your answer. (*Hint*: Can a football ever cast a circular shadow?)
- What is the difference between an Sa and an Sb galaxy? Between an S0 and an Sa galaxy? Between an Sb and an SBb galaxy? Between an E7 and an E0 galaxy?
- Why wouldn't white dwarfs make good distance indicators?
- Why isn't the look-back time important among nearby galaxies?
- Explain how the rotation curve method of finding a galaxy's mass is similar to the method used to find the masses of binary stars.
- Explain how the Hubble law allows you to estimate the distances to galaxies.
- How can collisions affect the shape of galaxies?
- What evidence can you cite that galactic cannibalism really happens?
- Describe the future evolution of a galaxy that astronomers now see as a starburst galaxy. What will happen to its interstellar medium?
- Why does the gas held in a cluster of galaxies help determine the nature of the galaxies in a cluster?
- How Do We Know?** Classification helped Darwin understand how creatures evolve. How has classification helped you understand how galaxies evolve?

Discussion Questions

- From what you know about star formation and the evolution of galaxies, do you think irregular galaxies should be bright or faint in the infrared? Why or why not? What about starburst galaxies? What about elliptical galaxies?
- Imagine that you could observe a few gas clouds at such a high look-back time that they are just beginning to form one of the first galaxies. Further, suppose you discovered that the gas was metal rich. Would that support or contradict your understanding of galaxy formation?

Problems

- If a galaxy contains a type I (classical) Cepheid with a period of 30 days and an apparent magnitude of 20, what is the distance to the galaxy? (*Hints*: See Figure 12-4 and the definition of distance modulus in Chapter 9.)
- If you find a galaxy that contains globular clusters that are 2 arc seconds in diameter, how far away is the galaxy? (*Hints*: Assume that a globular cluster is 25 pc in diameter and use the small-angle formula in Chapter 3.)
- If a galaxy contains a supernova that at its brightest has an apparent magnitude of 17, how far away is the galaxy? (*Hint*: Assume that the absolute magnitude of the supernova is -19 and see the definition of distance modulus in Chapter 9.)
- If you find a galaxy that is the same size and mass as our Milky Way Galaxy, what orbital velocity would a small satellite galaxy have if it orbited 50 kpc from the center of the larger galaxy? (*Hint*: See Chapter 15.)
- Find the orbital period of the satellite galaxy described in Problem 4.
- If a galaxy has an apparent radial velocity of 2000 km/s and the Hubble constant is 70 km/s/Mpc, how far away is the galaxy? (*Hint*: Use the Hubble law.)

- If you find a galaxy that is 20 arc minutes in diameter and you measure its distance to be 1 Mpc, what is its diameter?
- Suppose you found a galaxy in which the outer stars have orbital velocities of 150 km/s. If the radius of the galaxy is 4 kpc, what is the orbital period of the outer stars? (*Hints*: $1 \text{ pc} = 3.08 \times 10^{13} \text{ km}$, and $1 \text{ yr} = 3.16 \times 10^7 \text{ seconds}$.)
- A galaxy has been found that is 5 kpc in radius and whose outer stars orbit the center with a period of 200 million years. What is the mass of the galaxy? On what assumptions does this result depend?
- Among the globular clusters orbiting a distant galaxy, the fastest is traveling 420 km/s and is located 11 kpc from the center of the galaxy. Assuming the globular cluster is just barely gravitationally bound to the galaxy, what is the mass of the galaxy? (*Hint*: The galaxy had a slightly faster globular cluster, but it escaped some time ago. What is the escape velocity?)

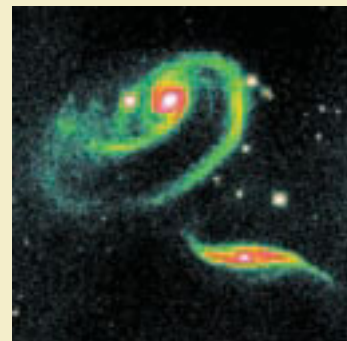
Learning to Look

- Study Figure 16-2. Which galaxies do you suppose are the nearest ones, and which are farthest away? How is your estimate based on your own calibration of galaxy size and luminosity?
- Hubble's first determination of the Hubble constant was too high because the calibration of Cepheid variable stars he used was not very good. Use his original diagram shown in Figure 16-5 to estimate his first determination of the Hubble constant.
- This image of M33 has emission by ionized hydrogen enhanced as bright pink. Discuss the location of these clouds of gas and explain how that provides important evidence toward understanding spiral arms.



P. Massey, Lowell Obs.; N. King, STScI; S. Holmes, College of Charleston; G. Jacoby, WITYN/AURA/NSF

- In the image at right you see two interacting galaxies; one is nearly face-on and the other is nearly edge-on. Discuss the shapes of these galaxies and describe what is happening.



WITYN/NOAO/AURA/NSF

17

Active Galaxies and Supermassive Black Holes



Visual (white) + radio (orange)

Size of Milky Way Galaxy

Guidepost

In the last few chapters, you have explored our own and other galaxies, and now you are ready to stretch your scientific imagination and study some of the most powerful objects in nature. Supermassive black holes at the centers of galaxies are common but extreme. To study them, you will be combining many of the ideas you have discovered so far to answer four essential questions:

— **What makes some galaxy cores active?**

— **How do supermassive black holes erupt?**

— **How did supermassive black holes form and evolve?**

— **How do supermassive black holes affect the evolution of their host galaxies and galaxy clusters?**

The formation and evolution of supermassive black holes leads your astronomical curiosity outward into space and backward in time to the era of galaxy formation. In the next chapter, you will take the next step and try to understand the birth and evolution of the entire universe.

Like cosmic fireworks, the galaxy NGC 1316 (Fornax A) has erupted to expel two lobes visible at radio wavelengths. The size of the Milky Way Galaxy is shown for comparison. (Image courtesy of Barbara Harris)

Somewhere something incredible is waiting to be known.

— CARL SAGAN

SUPERMASSIVE BLACK holes containing millions or even billions of solar masses lurk at the centers of many galaxies. Such monsters can release tremendous energy and cause eruptions that dwarf the largest supernovae. Yet most supermassive black holes in galaxy centers are not erupting. Why? The study of supermassive black holes will introduce you to some of the most extreme conditions in the universe.

17-1 Active Galactic Nuclei

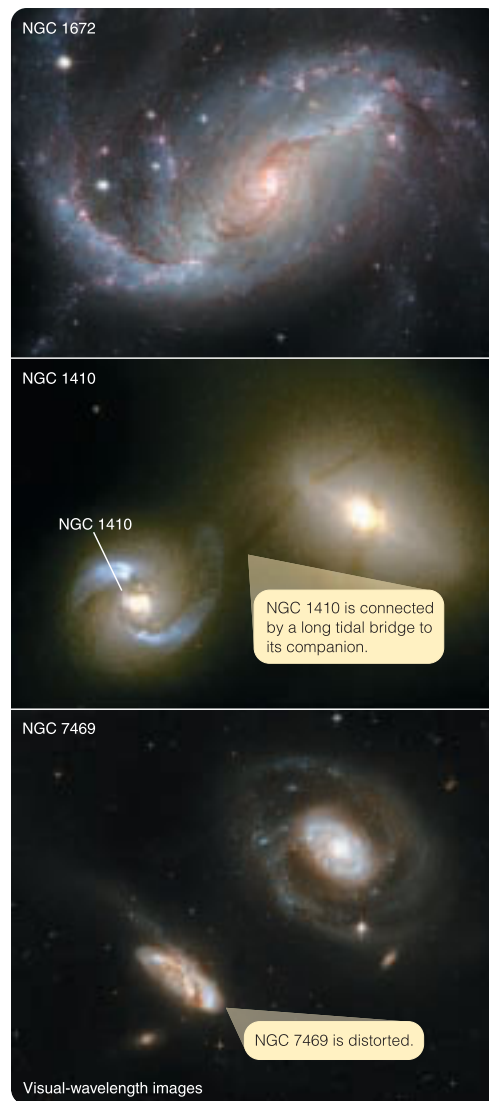
WITH THE CONSTRUCTION of the first large radio telescopes in the 1950s, astronomers discovered that some galaxies, dubbed **radio galaxies**, were bright at radio wavelengths. Later, when telescopes went into orbit, these galaxies were found to be emitting energy at other wavelengths as well, and they became known as **active galaxies**. Modern observations show that the energy comes from the nuclei of the galaxies, which are now known as **active galactic nuclei (AGN)**. Only a few percent of galaxies are active, so your first step is to meet these peculiar galaxies.

Seyfert Galaxies

In 1943, Mount Wilson astronomer Carl Seyfert published a study of spiral galaxies. Observing at visual wavelengths, Seyfert found that some spiral galaxies have small, highly luminous nuclei with peculiar spectra (■ Figure 17-1). These galaxies are now known as **Seyfert galaxies**.

The spectrum of a galaxy is the blended spectra of billions of stars, and consequently weak spectral lines get washed out. Galaxy spectra contain only a few of the strongest absorption lines found in stellar spectra. But spectra of Seyfert galaxy nuclei contain broad emission lines. Emission lines are produced by a hot, low-density gas, so the gas in the nuclei of Seyfert galaxies must be highly excited. The width of the spectral lines suggests large Doppler shifts produced by high velocities in the nuclei; gas approaching Earth produces blue-shifted spectral lines, and gas going away produces redshifted lines. The combined light of gas approaching and receding, therefore, contains broad spectral lines showing that the velocities at the center of Seyfert galaxies are roughly 10,000 km/s, about 30 times greater than velocities at the center of normal galaxies. Something violent is happening in the cores of Seyfert galaxies.

About 2 percent of spiral galaxies appear to be Seyfert galaxies, and they are classified into two categories. Type 1 Seyfert galaxies are very luminous at X-ray and ultraviolet wavelengths and have the typical broad emission lines with sharp, narrow cores. Rapidly moving gas produces the broad part of the lines, but some lower-velocity gas must also be present to produce the



■ **Figure 17-1**

Seyfert galaxies are spirals with small, highly luminous nuclei. Some are interacting with nearby companions and appear distorted with tidal tails and bridges. (All images: NASA, ESA, Hubble Heritage Team, STScI/AURA-ESA/Hubble Collaboration; NGC 1410: Wm. Keel, Univ. of Alabama; NGC 7469: A. Evans, Univ. of Virginia, NRAO/Stony Brook)

narrow cores. Type 2 Seyfert galaxies have much weaker X-ray emission and have emission lines that are narrower than those of type 1 Seyfert galaxies but still broader than spectral lines produced by a normal galaxy.

The brilliant nuclei of Seyfert galaxies fluctuate rapidly, especially at X-ray wavelengths. A Seyfert nucleus can change its X-ray brightness by a significant amount in only minutes. As you learned when you studied neutron stars, an object cannot change its brightness in a time shorter than the time it takes light to cross its diameter. If the Seyfert nucleus can change in a few minutes, then it cannot be more than a few light-minutes in diameter—about the size of Earth's orbit. In spite of their small size, the cores of

Statistical Evidence

How can statistics be useful if they can't be specific? Some scientific evidence is statistical. Observations suggest, for example, that Seyfert galaxies are more likely to be interacting with a nearby companion than a normal galaxy is. This is statistical evidence, so you can't be certain that any specific Seyfert galaxy will have a companion. How can scientists use statistical evidence to learn about nature when statistics contain built-in uncertainty?

Meteorologists use statistics to determine how frequently storms of a certain size are likely to occur. Small storms happen every year, but medium-sized storms may happen on average only every ten years. Hundred-year storms are much more powerful but occur much less frequently—on average only once in a hundred years.

Those meteorological statistics can help you make informed decisions—as long as you understand the powers and limitations of

statistics. Would you buy a house protected from a river by a levee that was not designed to withstand a hundred-year storm? In any one year, the chance of your house being destroyed would be only 1 in 100. You know the storm will hit eventually, but you don't know when. If you buy the house, a storm might destroy the levee the next year, but you might own the house for your whole life and never see a hundred-year storm. The statistics can't tell you anything about a specific year.

Before you buy that house, there is an important question you should ask the meteorologists. "How much data do you have on storms?" If they have only ten years of data, then they don't really know much about hundred-year storms. If they have three centuries of data, then their statistical data are significant.

Sometimes people dismiss important warnings by saying, "Oh, that's only statistics." Scientists can use statistical



Statistics can tell you that a bad storm will eventually hit, but it can't tell you when. (Marko Georgiev/Getty Images)

evidence if it passes two tests. It cannot be used to draw conclusions about specific cases, and it must be based on large enough data samples so the statistics are significant. With these restrictions, statistical evidence can be a powerful scientific tool.

Seyfert galaxies produce tremendous amounts of energy. The brightest emit a hundred times more energy than the entire Milky Way Galaxy.

Lots of energy is produced in a very small volume with extremely high temperatures and velocities. What does that remind you of? Astronomers conclude that the centers of these galaxies contain supermassive black holes orbited by hot accretion disks through which matter is flowing into the black hole.

In the previous chapter, you saw evidence that most galaxies contain supermassive black holes at their centers. But most

galaxies are not erupting. The shapes of Seyfert galaxies provide an important clue. About 25 percent of Seyfert galaxies have peculiar shapes suggesting that they have had tidal interactions with other galaxies (■ Figure 17-2). There is also statistical evidence (**How Do We Know? 17-1**) that Seyfert galaxies are more common in interacting pairs of galaxies than in isolated galaxies. These clues hint that Seyfert galaxies may have been triggered into activity by collisions or interactions with companions. You will find more such evidence as you study other kinds of active galaxies.



■ **Figure 17-2**

(a) The Seyfert galaxy NGC 7674 is part of a small, compact group of galaxies and is interacting with its smaller companion. Tidal tails are visible extending to the left and to the upper right. (b) The tidal tails are more easily visible in this enhanced image. (a: NASA, ESA, Hubble Heritage Team, STScI/AURA-ESA/Hubble Collaboration and A. Evans, Univ. of Virginia, NRAO/Stony Brook; b: John W. Mackenty, Institute for Astronomy, University of Hawaii)

Double-Lobed Radio Sources

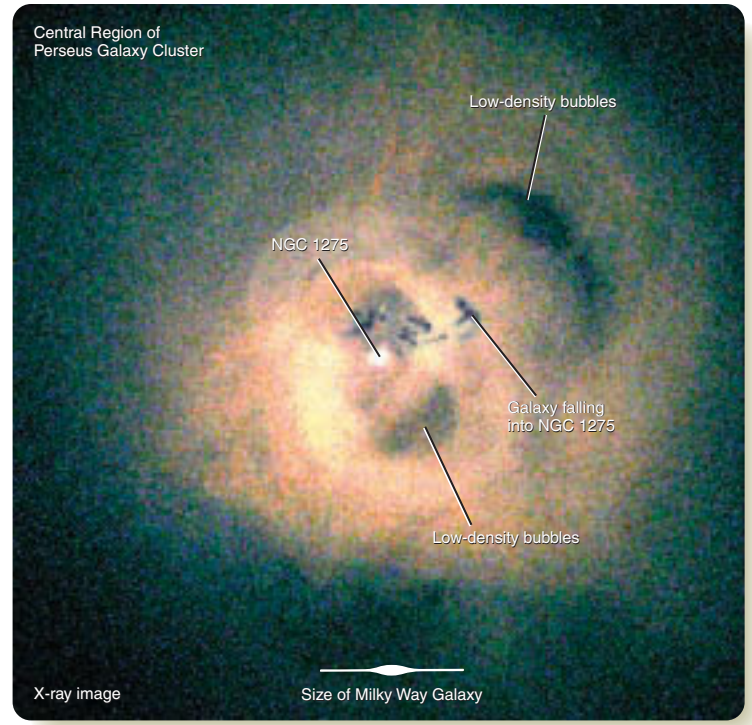
Beginning in the 1950s, radio astronomers found that some sources of radio energy in the sky consisted of pairs of radio-bright regions. When optical telescopes studied the locations of these radio sources, they revealed galaxies located between the two regions emitting radio energy, and the galaxies were dubbed **double-lobed radio galaxies**. Unlike Seyfert galaxies, which emit intense radiation from their cores, these radio galaxies are producing energy from two external radio lobes.

Study **Cosmic Jets and Radio Lobes** on pages 360–361 and notice four important points and two new terms:

- 1 The shapes of radio lobes suggest that they are inflated by jets of excited gas emerging from the nucleus of the central galaxy. This has been called the *double-exhaust model*. The presence of *hot spots* and synchrotron radiation shows that the jets are very powerful.
- 2 Active galaxies that have jets and radio lobes are often deformed or interacting with other galaxies.
- 3 The complex shapes of some jets and radio lobes can be explained by the motions of the active galactic nuclei. A good example of this is 3C 31 (the 31st source in the *Third Cambridge Catalog of Radio Sources*) with its twisting radio lobes.
- 4 These jets are consistent with matter falling into a central supermassive black hole. You have seen similar jets produced by accretion disks around protostars, neutron stars, and stellar mass black holes; although the details are not entirely understood, the same process seems to be producing all of these jets.

The evidence shows that the cores of many galaxies are occupied by supermassive black holes with matter flowing inward. As the matter falls toward the center, it releases tremendous gravitational energy and becomes intensely hot. The hot accretion disks can emit X-rays and eject jets in opposite directions.

In fact, the violence of these active galaxies is so great it can influence entire clusters of galaxies. The Perseus galaxy cluster contains thousands of galaxies and is one of the largest objects in the universe. One of its galaxies, NGC 1275, is one of the largest galaxies known. It is pumping out jets of high-energy particles, heating the gas in the galaxy cluster, and inflating low-density bubbles that distort the huge gas cloud (■ Figure 17-3). The hot gas observed in galaxy clusters is heated to multimillion-degree temperatures as galaxy after galaxy goes through eruptive stages that can last for hundreds of millions of years. NGC 1275 is erupting now, and it is so powerful and has heated the surrounding gas so hot that it may temporarily interrupt supply of gas to its central supermassive black hole, eventually choking off the eruption and curtailing further growth of the black hole. Astronomers speculate that there may be a



■ **Figure 17-3**

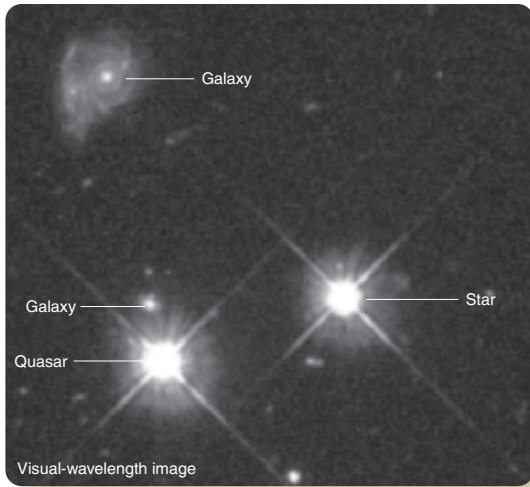
Active galaxy NGC 1275, also known as radio source Perseus A, lies in the Perseus galaxy cluster and is spewing out jets and streamers of high-energy particles that are inflating low-density cavities in the hot gas. Galaxy clusters commonly contain such hot gas, and active galaxies may be the main source of energy that heats the gas. The entire galaxy cluster is roughly 50 times larger in diameter than this image. (NASA/CXC/IoA/A. Fabian et al.)

maximum size for supermassive black holes set by this cycle of self-limiting activity.

Quasars

Through the 1950s, radio astronomers became familiar with celestial radio sources that were either huge clouds of gas or distant radio galaxies, so they were surprised in the early 1960s when some radio sources turned out to look like stars in visual-wavelength photographs (■ Figure 17-4). First called quasi-stellar objects, they were soon referred to as **quasars**. Many more quasars have been found over the years, and most are radio silent. The radio astronomers stumbled over those emitting radio energy because they were easy to notice. From their discovery, quasars have been a puzzle to astronomers.

The spectra of quasars were strange in that they contained a few unidentified emission lines superimposed on a continuous spectrum. In 1963, Maarten Schmidt at Hale Observatories tried redshifting the hydrogen Balmer lines to see if they could be made to agree with the lines in the spectrum of the quasar known as 3C 273. At a redshift of 15.8 percent, three lines clicked into place (■ Figure 17-5). Other quasar spectra quickly yielded to this approach, revealing even larger redshifts.



■ **Figure 17-4**

Quasars have starlike images clearly different from the images of even very distant galaxies. Although quasars look like stars, their spectra are unlike the spectra of stars or galaxies. The spikes on these images were produced by diffraction in the telescope. (C. Steidel, Caltech, NASA)

Numerically the redshift z is the change in wavelength $\Delta\lambda$ divided by the unshifted wavelength λ_0 :

$$\text{redshift} = \frac{\Delta\lambda}{\lambda_0}$$

According to the Hubble law, these large redshifts imply very large distances. The first quasars studied were the brighter ones, but surveys have found many more. For example, the Sloan

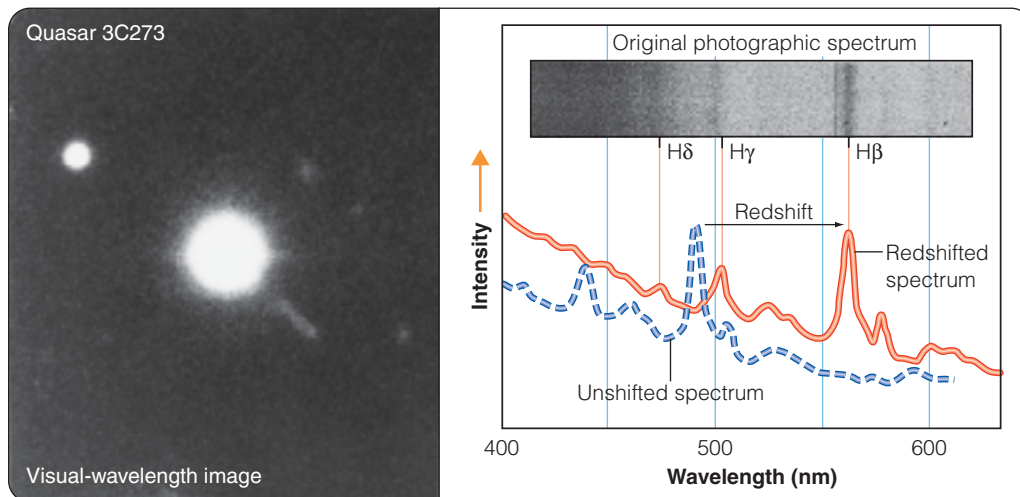
Digital Sky Survey discovered 90,000. Most of these quasars have very high redshifts and lie very far from Earth.

Many quasar redshifts are greater than 1.0, and that may strike you as impossible. The Doppler formula implies that such objects must have velocities greater than the speed of light. But the redshifts of the galaxies and quasars are not produced by the Doppler effect. As you will discover in the next chapter, the redshifts are produced by the expansion of the universe, and astronomers must use the equations of general relativity to interpret them. Redshifts greater than 1.0 are not a problem and merely indicate great distance.

Although the quasars are far away, they are not very faint. A typical galaxy at such a distance would be faint and extremely difficult to detect, but quasars show up on photographs as noticeable points of light. If you put the apparent brightnesses and huge distances of quasars into the magnitude–distance relation, you will discover that quasars are ultraluminous, having 10 to 1000 times the luminosity of a large galaxy.

Soon after quasars were discovered, astronomers detected fluctuations in brightness over times as short as a few hours. Those rapid fluctuations show that quasars are small objects, not more than a few light-hours in diameter—smaller than our solar system.

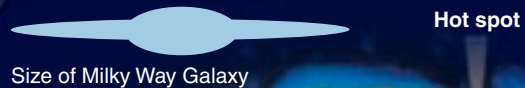
By the late 1960s, astronomers trying to understand quasars faced a problem: How could quasars be ultraluminous but also very small? What could make 10 to 1000 times more energy than a galaxy in a region as small as our solar system? Since that time, new, large telescopes in space and on Earth’s surface have revealed



■ **Figure 17-5**

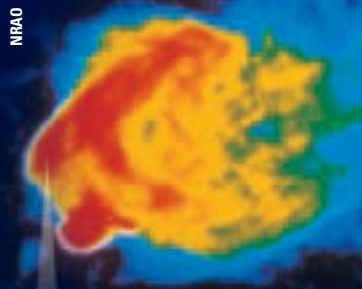
This image of 3C 273 shows the bright quasar at the center surrounded by faint fuzz. Note the jet protruding to lower right. The original photographic plate holding a spectrum of 3C 273 contains three hydrogen Balmer lines, H_δ , H_γ , and H_β . The spectrum is redshifted by 15.8 percent. The dashed line shows the unshifted position of the spectrum. (Image and photographic spectrum courtesy of Maarten Schmidt)

Cosmic Jets and Radio Lobes



1 Many radio sources consist of two bright lobes — double-lobed radio sources — with a galaxy, often a peculiar or distorted galaxy, located between them. Evidence suggests these active galaxies are emitting jets of high-speed gas that inflate the lobes as cavities in the intergalactic medium. This has been called the **double-exhaust model**. Where the jets impact the far side of the cavities, they create **hot spots**.

NRAO



Hot spot

1a Cygnus A, the brightest radio source in Cygnus, is a pair of lobes with jets leading from the nucleus of a highly disturbed galaxy. In this false-color image, the areas of strongest radio signals are shown in red and the weakest in blue. Because the radio energy detected is synchrotron radiation, astronomers conclude that the jets and lobes contain very-high-speed electrons, usually called relativistic electrons, spiraling through magnetic fields about 1000 times weaker than Earth's field. The total energy in a radio lobe is about 10^{53} J — what you would get if you turned the mass of a million suns directly into energy.

Radio image

Jet

Jet

Hot spots lie on the leading edge of a lobe where the jet pushes into the surrounding gas.

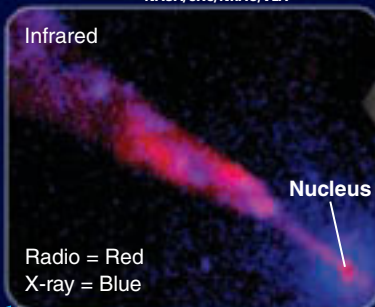


Visible galaxy

Used with permission, Fosbury R. A. E., Vernet, J., Villar-Martin, M., Cohen, M. H., Ogle, P. M., Tran, H. D. & Hook, R. N. 1998, Optical continuum structure of Cygnus A. "KNAW colloquium on: The most distant radio galaxies," Amsterdam, 15-17 October 1997, Roettgering, H., Best, P., and Lehnert, M. eds (Reidel).

2 The radio galaxy NGC 5128 lies between two radio lobes, and, like many active galaxies, is strangely distorted. The dust ring rotates about an axis perpendicular to the ring, but the spherical cloud of stars rotates about an axis that lies in the plane of the ring. NGC 5128 appears to be two galaxies, a giant elliptical and a spiral, passing through each other. This has triggered multiple eruptions. An earlier eruption has produced a large outer pair of lobes, and a more recent eruption has produced an inner pair.

NASA/CXC/NRAO/VLA



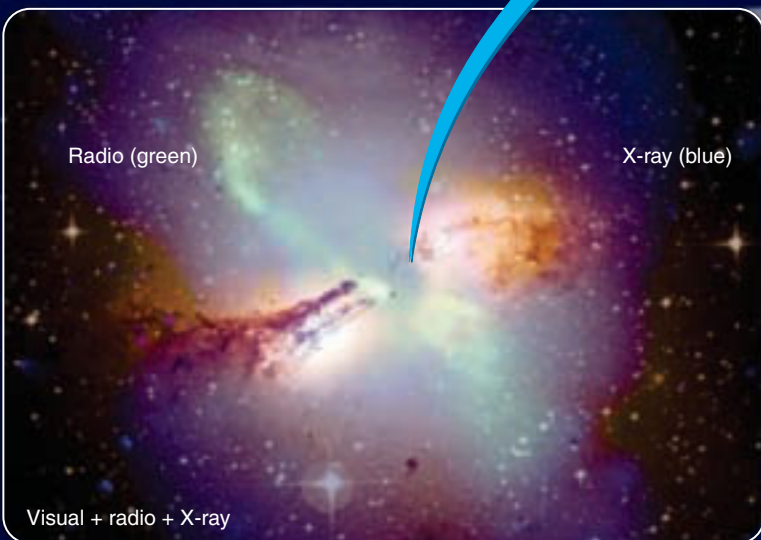
Infrared

Nucleus

Radio = Red
X-ray = Blue

The combined radio and X-ray image at the left shows a high-energy jet at the very center of the galaxy pointing to the upper left into the northern radio lobe.

X-ray: NASA/CXC/M. Karovska et al., Radio: NRAO/VLA/Schiminovich, et al., Radio: NRAO/VLA/J. Condon et al., Optical: Digitized Sky Survey U.K. Schmidt Image/STScI.



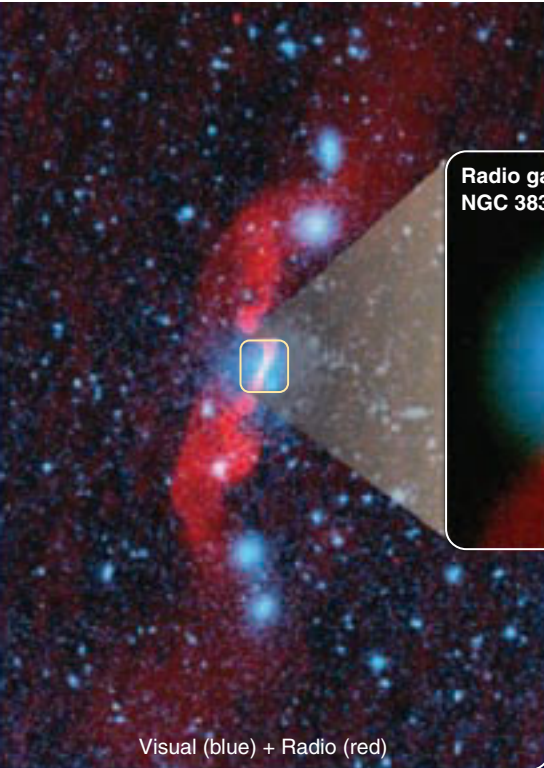
Radio (green)

X-ray (blue)

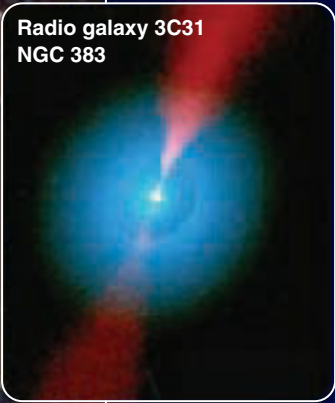
Visual + radio + X-ray

If the outer radio lobes of Centaurus A were visible to your eyes, they would look 10 times larger than the full moon.





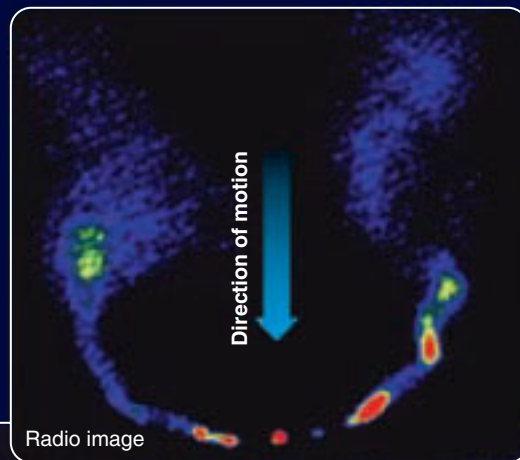
Visual (blue) + Radio (red)



Radio galaxy 3C31
NGC 383

NRAO/AUI/NSF

3 The radio jets from NGC 1265 are being left behind as the galaxy moves rapidly through the gas of the intergalactic medium. Twists in the tails are presumably caused by motions of the active nucleus.



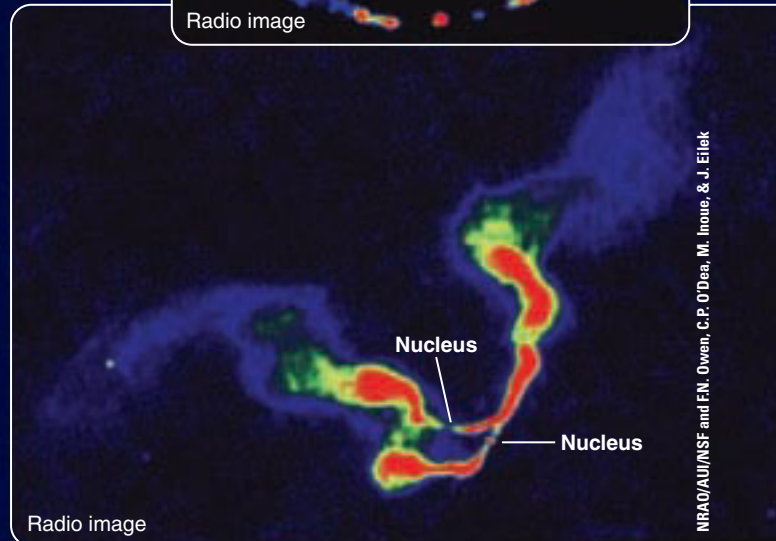
Radio image

Direction of motion

NRAO/AUI/NSF and C. O'Dea & F. Owen

3a Radio galaxy 3C31 is one of a chain of galaxies. It has ejected jets from its core that twist, presumably because the active nucleus is orbiting another object such as the nucleus of a recently absorbed galaxy.

3b The radio source 3C75 is produced by two galaxies experiencing a close encounter. As the active nuclei whip around each other, their jets twist and turn. The size of the visible galaxies would be about the size of cherries at the scale of this image.



Radio image

Nucleus

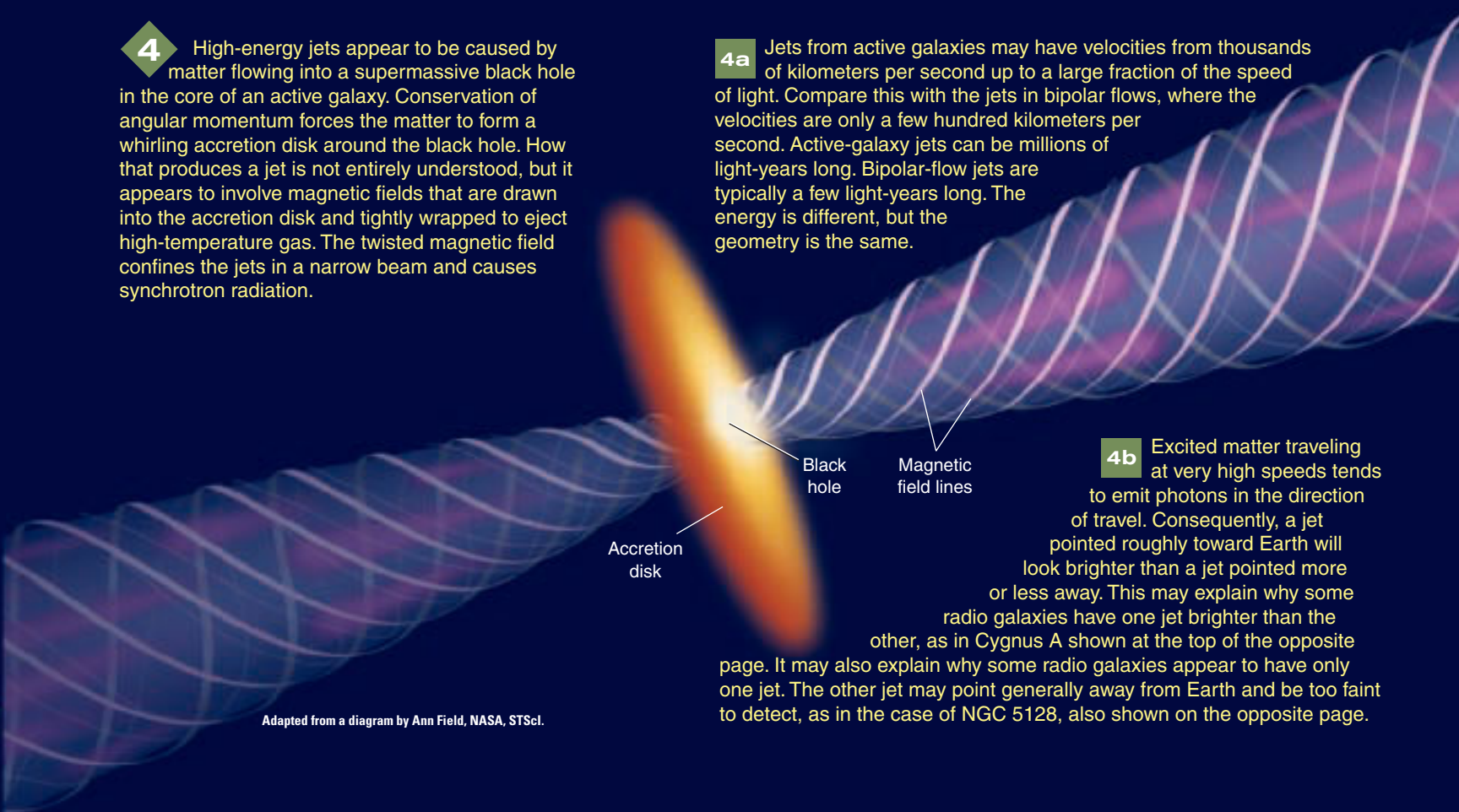
Nucleus

NRAO/AUI/NSF and F.N. Owen, C.P. O'Dea, M. Inoue, & J. Eilek

4 High-energy jets appear to be caused by matter flowing into a supermassive black hole in the core of an active galaxy. Conservation of angular momentum forces the matter to form a whirling accretion disk around the black hole. How that produces a jet is not entirely understood, but it appears to involve magnetic fields that are drawn into the accretion disk and tightly wrapped to eject high-temperature gas. The twisted magnetic field confines the jets in a narrow beam and causes synchrotron radiation.

4a Jets from active galaxies may have velocities from thousands of kilometers per second up to a large fraction of the speed of light. Compare this with the jets in bipolar flows, where the velocities are only a few hundred kilometers per second. Active-galaxy jets can be millions of light-years long. Bipolar-flow jets are typically a few light-years long. The energy is different, but the geometry is the same.

4b Excited matter traveling at very high speeds tends to emit photons in the direction of travel. Consequently, a jet pointed roughly toward Earth will look brighter than a jet pointed more or less away. This may explain why some radio galaxies have one jet brighter than the other, as in Cygnus A shown at the top of the opposite page. It may also explain why some radio galaxies appear to have only one jet. The other jet may point generally away from Earth and be too faint to detect, as in the case of NGC 5128, also shown on the opposite page.



Adapted from a diagram by Ann Field, NASA, STScI.

that quasars are often surrounded by hazy features whose spectra resemble those of normal galaxies. Evidently, quasars are located in galaxies. In addition, radio telescopes have revealed that some quasars are ejecting jets and inflating radio lobes. The evidence is now overwhelming that quasars are the active cores of very distant galaxies. In other words, quasars are the most extreme kind of active galactic nuclei.

SCIENTIFIC ARGUMENT

What evidence suggests that radio lobes are inflated by jets from the nucleus?

Of course, the strongest evidence is that in a few cases, a jet is actually detectable at visual or radio wavelengths leading from the center of a galaxy out into a radio lobe. But astronomers also note that hot spots occur on the outer edges of many radio lobes where a jet, whether it is visible or not, would collide with the intergalactic medium. In some cases where jets are detectable, they are curved and twisted by the orbital motion of the nucleus, which shows that they are being produced by gas expelled from the nucleus.

Evidence is the key to understanding science. Now create a new scientific argument to answer the following: **What evidence suggests that active galaxies contain accretion disks orbiting central supermassive black holes?**

17-2 Supermassive Black Holes

IN THE PREVIOUS TWO CHAPTERS, you learned that many galaxies contain supermassive black holes at their centers. Why do such objects produce eruptions, and how did they form?

Disks and Jets

Matter flowing inward toward a black hole spins very fast and becomes very hot. It spins because it must conserve angular momentum as it sinks inward where it forms a flattened disk around the central black hole. Supermassive black holes have stronger gravity than stellar-mass black holes and produce faster spins for the in-falling matter and higher temperatures. Even a supermassive black hole is surprisingly small. A 10-million-solar-mass black hole would be only one-fifth the diameter of Earth's orbit, so the matter can get close to the black hole and orbit very fast. The in-falling matter heats up because it picks up speed; and, as it collides with other matter, those high velocities become thermal energy. That is, matter falling inward converts gravitational energy into thermal energy and becomes hot.

Theoretical calculations predict that the high temperature “puffs up” the inner part of the disk and makes it thick. Closer to the black hole, an orbiting particle is unstable and must spiral into the black hole, so the black hole is hidden deep inside an empty central well. Farther out, the disk is thinner and cooler, but the outermost part of the disk, according to calculations, is a fat, cool torus (doughnut shape) of dusty gas.

Astronomers can't see black holes, but in some active galaxies, the Hubble Space Telescope can detect the outer parts of the central disks (■ Figure 17-6). Spectra reveal the speed of rotation, and Kepler's third law yields the mass of the central object. Some supermassive black holes have masses of a few million solar masses, like the one in the center of our Milky Way Galaxy, but the most massive contain billions of solar masses.

The inner part of the accretion disk around a supermassive black hole can reach temperatures of millions of degrees and emit X-rays. In fact, cosmic ray detectors on Earth have observed ultra-high-energy particles that come from places in the sky occupied by active galactic nuclei. These powerful supermassive black holes and their hot accretion disks may be filling the universe with high-speed particles packing the wallop of major league fastballs.

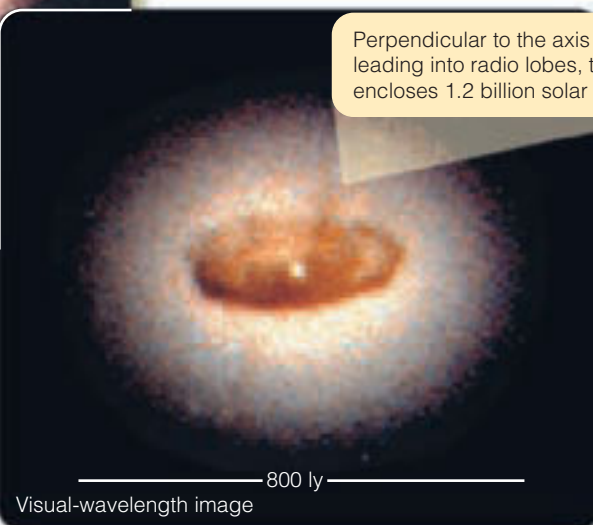
No one knows exactly how the supermassive black hole and its disk produce jets of gas and radiation, but magnetic fields are a factor. Because the disk is at least partially ionized, magnetic fields are trapped in the gas of the disk, drawn inward, and wound up. Theorists suggest that this creates powerful magnetic tubes extending along the axis of rotation, channeling hot gas



■ **Figure 17-6**

The elliptical galaxy NGC 4261 is ejecting jets and inflating radio lobes. High-resolution images show that the core contains a small, bright nucleus orbited by a spinning disk. The orbital velocity and size of the disk confirm that the central object is a supermassive black hole. (L. Ferrarese, Johns Hopkins University, and NASA)

Perpendicular to the axis of the jets leading into radio lobes, this disk encloses 1.2 billion solar masses.



outward in opposite directions. The jets seem to originate very close to the supermassive black hole and are then focused and confined by the enclosing magnetic tubes.

The mechanism that produces jets is understood in only a general way, but astronomers are now trying to work out the details. How can supermassive black holes explain all of the different kinds of active galaxies that are observed?

The Search for a Unified Model

When a field of research is young, scientists find many seemingly different phenomena, such as Seyfert galaxies, double-lobed radio galaxies, quasars, cosmic jets, and so on. As the research matures, scientists begin seeing similarities and eventually are able to unify the different phenomena as different aspects of a single process. This organization of evidence and theory into logical arguments that explain how nature works is the real goal of science. Astronomers studying active galaxies have developed

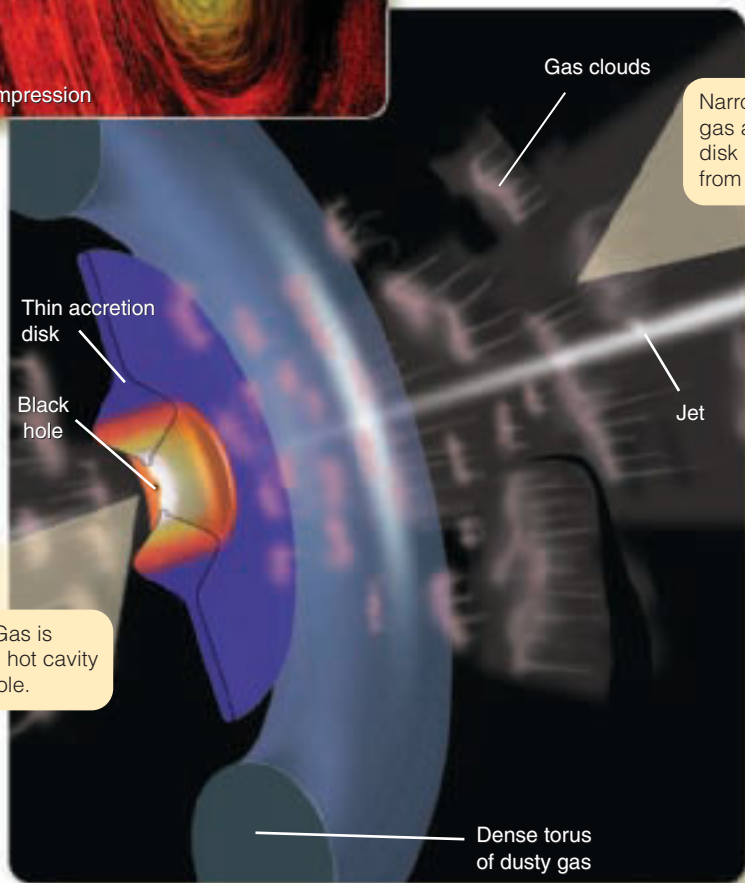
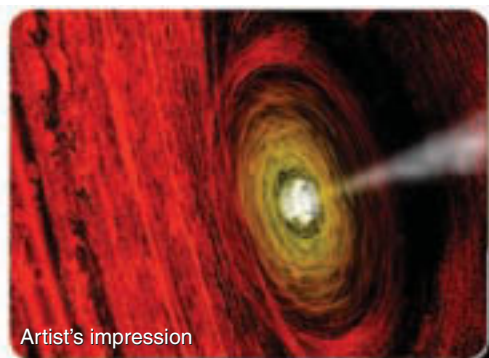
a **unified model** of active galaxy cores that is well supported by evidence. A monster black hole is the centerpiece.

According to the unified model, what you see when you view the core of an active galaxy depends on how the black hole's accretion disk is tipped with respect to your line of sight. You should note that the accretion disk may be tipped at a steep angle to the plane of its galaxy, so just because you see a galaxy face-on doesn't mean you are looking at the accretion disk face-on.

If you view the accretion disk edge-on, you cannot see the central area at all because the thick dusty torus blocks your view. Instead, you see gas lying above and below the central disk, gas that is excited by intense radiation coming from the black hole down in the central well. Because this gas is farther from the center, it is cooler, orbits more slowly, and has smaller Doppler shifts and thus narrower spectral lines (■ Figure 17-7). This might account for the type 2 Seyfert galaxies.

■ **Figure 17-7**

The features visible in the spectrum of an AGN depend on the angle at which it is viewed. The unified model, shown in cross section, suggests that matter flowing inward passes first through a large, opaque torus; then into a thinner, hotter disk; and finally into a small, hot cavity around the black hole. Telescopes viewing such a disk edge-on would see only narrow spectral lines from cooler gas, but a telescope looking into the central cavity would see broad spectral lines formed by the hot gas. This diagram is not to scale. The central cavity may be only 0.01 pc in radius, while the outer torus may be 1000 pc in radius. (Artist's impression: NASA)



Broad line region: Gas is hottest in the deep, hot cavity around the black hole.

Narrow line region: Cooler gas above and below the disk is excited by radiation from the hot, inner disk.

If the accretion disk is tipped slightly, you may be able to see some of the intensely hot gas in the central cavity. This region emits broad spectral lines because the hot gas is orbiting at high velocities and the high Doppler shifts smear out the lines. Type 1 Seyfert galaxies may be explained by this phenomenon.

What happens if you look directly into the central cavity? According to the unified model, you would be looking directly into the high-energy jet—down the dragon’s throat. A few such objects have been found; they have a featureless spectrum and fluctuate in brightness in only hours.

The unified model is far from complete. The actual structure of accretion disks is poorly understood, as is the process by which the disks produce jets. The unified model does not explain all of the differences among active galaxies and quasars. Rather, it is a model that provides some clues to what is happening in active galactic nuclei.

Triggering Eruptions

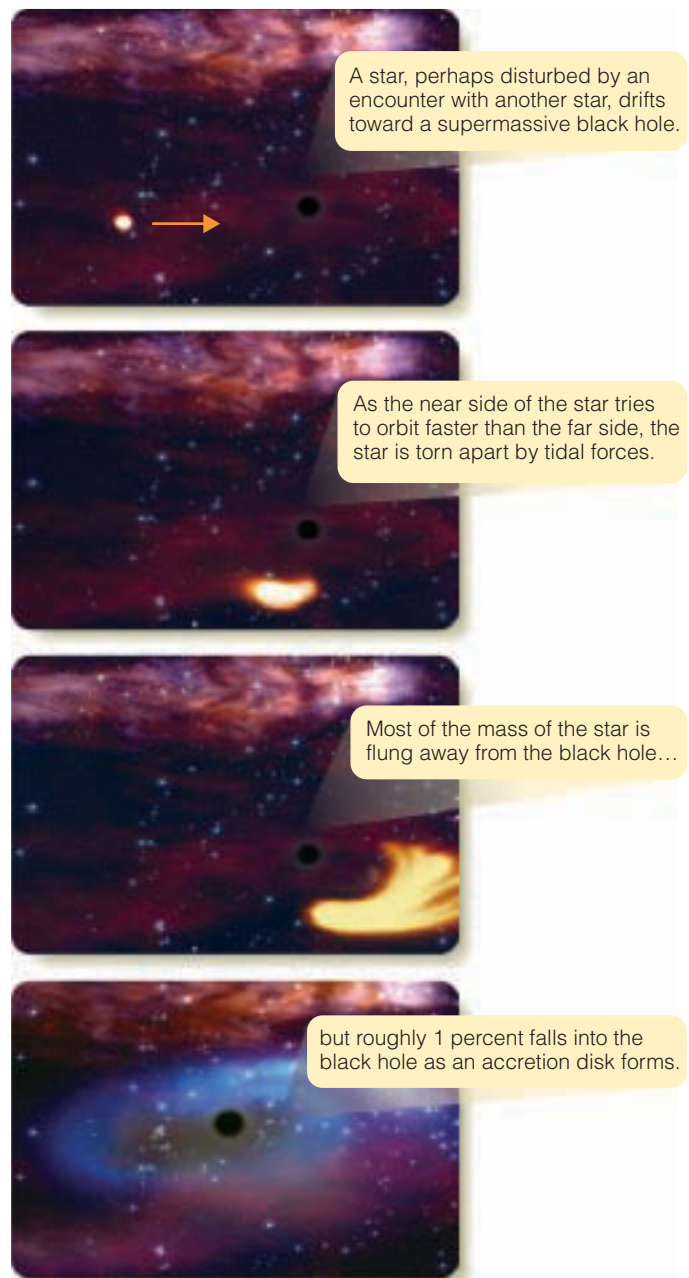
Most galaxies contain supermassive black holes at their centers, but only a few percent of galaxies have active galactic nuclei. That must mean that most of the supermassive black holes are dormant. They are sleeping.

What could trigger a supermassive black hole to erupt? The answer is something that you studied back in Chapter 5—tides. In the previous chapter you saw how tides twist interacting galaxies and rip matter away into tidal tails, but mathematical models show that those same interactions can also throw matter inward. A sudden flood of matter flowing into the accretion disk around a supermassive black hole would trigger it into eruption. This explains why active galaxies are often distorted; they have been twisted by tidal forces as they interacted or merged with another galaxy. Some active galaxies have nearby companions, and you can suspect that the companions are guilty of tidally distorting the other galaxy and triggering an eruption by tossing material into its central supermassive black hole.

Tidal forces between galaxies span distances of 100,000 ly or more, but the same bit of physics becomes important when matter comes very close to a supermassive black hole. ■ Figure 17-8 shows how a passing star would be ripped apart by tidal forces and at least partially consumed by a black hole. Inflowing gas, dust, and an occasional star would be an energy feast for a supermassive black hole.

Observations support the idea that galaxy interactions trigger active galactic nuclei. You have seen that many active galaxies are distorted. Images of some quasars reveal that they are embedded in galaxies that are distorted and lie near other distorted galaxies (■ Figure 17-9). Furthermore, in a survey of active galactic nuclei, over a third were found to originate in double objects. That is, the active nucleus is orbiting an object of similar mass. Evidently, these objects are the result of galaxy mergers in which the two original galaxies’ supermassive black holes have sunk to the center of the new combined galaxy and are spiraling toward each other.

Star Falling into a Black Hole

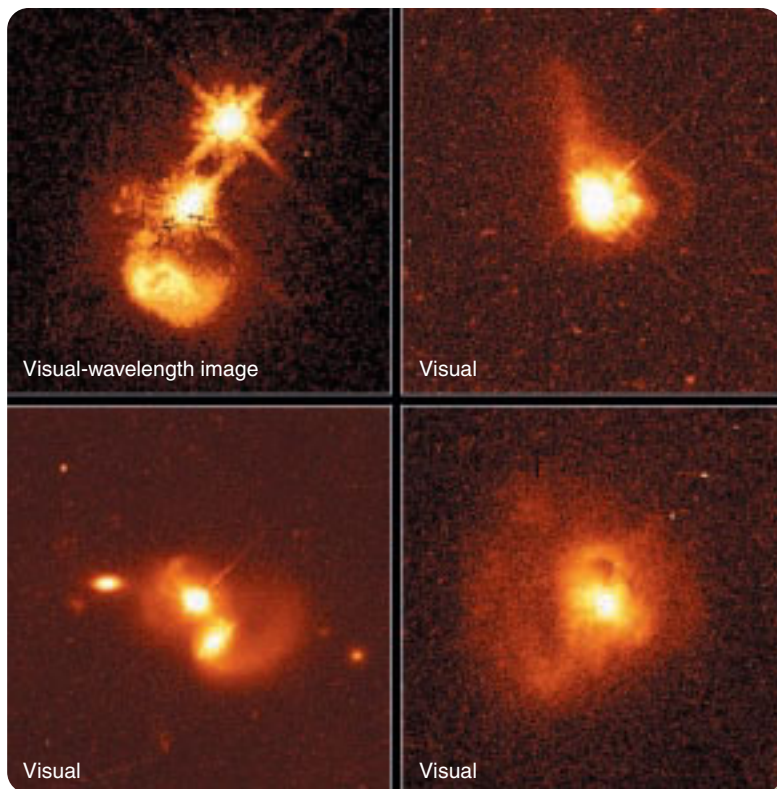


■ **Figure 17-8**

Orbiting X-ray telescopes observing active galaxies sometimes detect X-ray flares equaling the energy of a supernova explosion. Such flares are evidently caused when a star wanders too close to the supermassive black hole at the center of the galaxy and tidal forces rip the star apart. (ESA)

Supermassive Black Holes Through Time

When you look at a photo of galaxies with large redshifts, the look-back time is large, and you see the universe as it was long ago. The light journeying from such a great distance carries information about how the galaxies formed and developed.



■ **Figure 17-9**

The bright object at the center of each of these images is a quasar. Fainter objects around and near the quasars are galaxies distorted by collisions and tidal interactions. (J. Bahcall, Institute for Advanced Study, Mike Disney, University of Wales, NASA)

Astronomers have been able to measure the masses of a few dozen supermassive black holes by observing the speed of matter whirling around them. Interestingly, those masses are correlated with the masses of the host galaxies' central bulges. In each case, the mass of the black hole is about 0.5 percent the mass of the surrounding central bulge. But, for disk galaxies, there is no relationship between the masses of the black holes and the masses of the disks. This bit of statistics provides an intriguing insight into how galaxies formed soon after the universe began. Somehow, the formation process for supermassive black holes in the centers of galaxies was connected with the formation of their central bulges, but not their disks.

In the next chapter, you will see evidence that the universe began 13.7 billion years ago and that it has been expanding ever since. Within a few hundred million years, the first clouds of gas began forming stars and falling together to form the great star clouds that became the nuclear bulges of galaxies. The supermassive black holes formed at the same time. In fact, some evidence suggests that the black holes formed first and pulled matter inward to form central bulges. Matter flooding into these black holes would have triggered powerful outbursts, which because of the large look-back times could be visible from Earth today. The

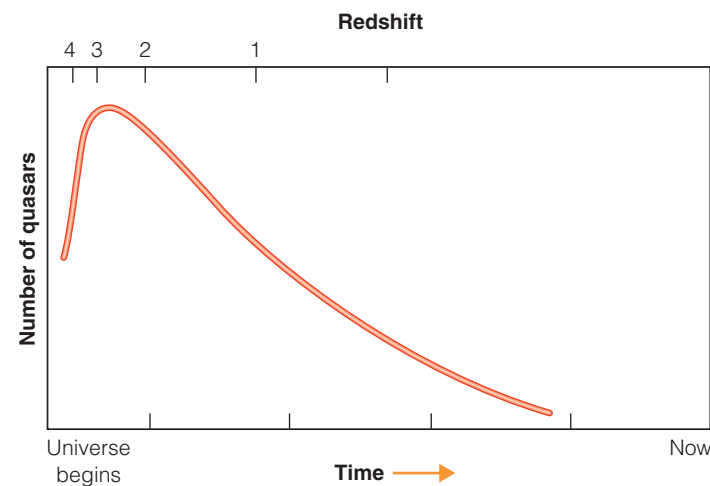
formation of a central bulge was evidently a violent process. Astronomers hypothesize that the increasing power of outbursts from the growing central black hole in a forming galaxy would have been able to push away infalling gas and limit the material available to form the stars of the central bulge.

In a spiral galaxy such as the Milky Way, the disk with its spiral arms and bright stars seems a dominant part of the galaxy. But recall from Chapter 15 that the disk formed late as matter gradually settled into the galaxy. By that stage, the central bulge and black hole had already formed, and the gradual development of the outer disk didn't trigger a violent eruption. "Disk formation is wimpy," said one astronomer.

Some of the most distant quasars could have been caused by the formation of supermassive black holes, but these extremely distant objects are difficult to image with existing telescopes. Most of the quasars and other active galaxies that astronomers see with today's telescopes have been triggered into eruption by the interaction and collision of galaxies, a process that throws matter into the central black holes. When the universe was young and had not expanded very much, galaxies were closer together and collided more often. Also, as small galaxies fell inward

and formed halos around larger galaxies (see Chapter 16), more matter would have been fed inward to the supermassive black holes and triggered more eruptions.

Astronomers have interpreted these observations to imply that in the first half of the history of the universe, each galaxy merged with other galaxies as often as three times every billion years. Most mergers were with smaller galaxies, but a few would have been with larger galaxies and triggered eruptions visible from Earth today as quasars.



■ **Figure 17-10**

At large look-back times, you see the universe as it was long ago. Between redshifts of about 2 and 3, you look back to a time when galaxies were closer together and were actively forming, merging, and interacting. That produced quasars. More recently, quasars have become less common.

Quasars are most common with redshifts over 2 and less common with redshifts above 3 (■ Figure 17-10). The largest quasar redshifts are over 6, but such high-redshift quasars are quite rare. Evidently astronomers see few quasars at high redshifts because they are looking back to an age when the universe was so young it had not yet formed many galaxies. At redshifts between about 2 and 3, galaxies were actively growing, colliding, and merging, and quasars were about 1000 times more common than they are now. Nevertheless, even during the age of quasars, quasar eruptions must have been unusual. At any one time, only a small fraction of galaxies had quasars erupting in their cores. As smaller galaxies were gobbled up and expansion of the universe (Chapter 18) carried the galaxies away from each other, galaxy formation became less active, interactions between galaxies became rare, and quasars became even less common.

“Then where are all the dead quasars?” an astronomer asked recently. “There is no way to get rid of supermassive black holes, so all of the galaxies that had short-lived quasars must still have those supermassive black holes.” Where are all those dead quasars today? You know where to look—the cores of galaxies.

Many galaxies, perhaps the majority of large galaxies, contain supermassive black holes at their centers, but the black holes have consumed most of the nearby gas, dust, and stars and are now dormant. Our own Milky Way Galaxy could have had a

quasar at its core long ago, but now its central supermassive black hole is on a strict diet. A slow trickle of matter flowing into the black hole could explain the mild activity seen there. Occasional interactions between galaxies can throw matter inward and nudge the dragon, awaking a sleeping supermassive black hole into eruption as a Seyfert galaxy or a double-lobed radio galaxy.

The active galaxies are not a rare kind of galaxy. They are normal galaxies passing through a stage that many galaxies experience: They are not really peculiar. They are an important part of the story of the formation and evolution of galaxies.

SCIENTIFIC ARGUMENT

What do the distorted shapes of active galaxies tell you?

Seyfert galaxies and the galaxies located between double radio lobes are often distorted and have tidal tails. Also, the galaxies that are faintly visible around quasars are also typically twisted out of shape. These distortions must be caused by tidal interactions with nearby galaxies or by mergers, and such tides can throw matter inward toward the supermassive black hole at the center of a galaxy and trigger an eruption.

Now build a new scientific argument. **Why were quasars rare when the universe was young, and why are they rare today?**

What Are We? Changed

Next time you are in a shopping mall, glance at the people around you. How many of them, do you suppose, know that galaxies can erupt or that there was an age of quasars? The vast majority of people have no idea how their lives fit into the story of the universe. Most people don't know what they are. They eat

pizza and watch TV without understanding that they are part of a universe in which galaxy collisions trigger supermassive black holes to erupt in titanic explosions.

Astronomy is changing you. As you learn more about stars and galaxies and quasars, you are learning more about yourself and

your connection with nature. “Perspective” can mean a view of things in their true relationships. As you study astronomy, you are gaining perspective. Our galaxy, our sun, our planet, and the local shopping mall take on new meaning when you think astronomically.

Study and Review

Summary

- ▶ First called **radio galaxies (p. 356)**, **active galaxies (p. 356)** are now known to emit energy at many wavelengths. Because the energy comes from their cores, they are known also as **active galactic nuclei (AGN) (p. 356)**.
 - ▶ **Seyfert galaxies (p. 356)** are spiral galaxies with small, highly luminous cores and spectra that show the nuclei contain highly excited gas.
 - ▶ **Double-lobed radio galaxies (p. 358)** emit radio energy from areas on either side of the galaxies. As described by the **double-exhaust model (p. 360)**, these lobes are inflated by jets ejected from the nuclei of the galaxies. Where the jets have an impact on surrounding gas, they form **hot spots (p. 360)**.
 - ▶ Jets from active galaxies are at least in part responsible for heating the gas trapped in clusters of galaxies.
 - ▶ The **quasars (p. 358)** have a starlike appearance but very large redshifts that imply they are very distant. To be visible at such distances, quasars must be ultraluminous. Yet rapid fluctuations in brightness show that quasars must be small, with diameters of only a few light hours, comparable in size to our solar system.
 - ▶ The best images show that quasars are embedded in galaxies that are often distorted or have close companions. From this, astronomers conclude that quasars are the highly luminous cores of very distant active galaxies.
 - ▶ Matter flowing into a supermassive black hole must conserve angular momentum and form an accretion disk. Observations indicate that these accretion disks are thick and dusty at great distances from the central black hole but thin and hot closer in. The closest part of the disk is puffed up, and the black hole is hidden deep in a cavity at the center. A few such disks have been imaged in the cores of active galaxies, and measurement of their rotation velocities permit determination of the masses of the black holes.
 - ▶ The spinning accretion disk pulls in and winds up the magnetic field, and by a process not yet fully understood, this magnetic field ejects and focuses two jets of radiation and high-speed gas in opposite directions along the axis of rotation.
 - ▶ Supermassive black holes erupt only when large amounts of matter flow inward, so most galaxies have dormant cores with little mass falling inward. During galaxy interactions and collisions, tides can throw matter into the galaxy centers and trigger eruptions. This explains why active galaxies are often distorted or have nearby companions.
 - ▶ Because quasars lie at great distances, astronomers see them as they were long ago—over 10 billion years ago—when the universe was young and just forming galaxies.
 - ▶ According to the **unified model (p. 363)**, what you see depends on the tilt of the accretion disk. If you see into the narrow cavity at the center, you see broad spectral lines produced by hot, high velocity gas. If you see the disk edge-on, you cannot see into the cavity and can detect only narrow spectral lines. If the jet from the black hole points directly at you, you see a featureless spectrum.
 - ▶ Because the mass of a supermassive black hole is related to the mass of the galaxy's central bulge around it, astronomers conclude that the black holes formed soon after the beginning of the universe when the first gas clouds fell together to form the central bulges.
 - ▶ Mergers with smaller galaxies are thought to have built the halos of galaxies and may have triggered eruptions of the cores. However, the formation of the large disks that lie outside the central bulges occurred as gas settled into the galaxies. That process was not violent and didn't trigger eruptions.
- ▶ Some of the most distant quasars may be erupting because of the formation of supermassive black holes, but most activity is triggered by interactions and collisions with other galaxies. Collisions were more common in the past before the universe had expanded very far and separated galaxies.
 - ▶ The age of quasars, at redshifts from about 2 to 3, was a time when galaxies were actively growing and merging.
 - ▶ The supermassive black holes that once produced quasar eruptions are now mostly dormant because very little mass is flowing into them. A galaxy can be triggered to become an active galaxy if new mass falls into the black hole.

Review Questions

1. What is the difference between the terms *radio galaxy* and *active galaxy*?
2. What statistical evidence suggests that Seyfert galaxies have suffered recent interactions with other galaxies?
3. What evidence shows that the energy source in a double-lobed radio galaxy lies at the center of the galaxy?
4. How does the peculiar rotation of NGC 5128 help explain the origin of this active galaxy?
5. What evidence shows that quasars are ultraluminous but must be small?
6. What evidence is there that quasars occur in distant galaxies?
7. How does the unified model explain the two kinds of Seyfert galaxies?
8. Why are there few quasars at low redshifts and at high redshifts but many at redshifts between about 2 and 3?
9. Why did galaxies collide more often in the distant past than they do now?
10. **How Do We Know?** How would you respond to someone who said, "Oh, that's only statistics"?

Discussion Questions

1. Why do quasars, active galaxies, SS 433, and protostars have similar geometry?
2. Astronomers normally refer to the unified *model* of AGN and not to the unified *hypothesis* or unified *theory*. In your opinion, which of the words seems best?
3. Do you think that our galaxy has ever been an active galaxy? Could it have hosted a quasar when it was young?

Problems

1. The total energy stored in a radio lobe is about 10^{53} J. How many solar masses would have to be converted to energy to produce this energy? (*Hints:* Use $E = mc^2$. One solar mass equals 2×10^{30} kg.)
2. If the jet in NGC 5128 is traveling at 5000 km/s and is 40 kpc long, how long will it take for gas to travel from the core of the galaxy to the end of the jet? (*Hint:* 1 pc equals 3×10^{13} km.)
3. Cygnus A is roughly 225 Mpc away, and its jet is about 50 arc seconds long. What is the length of the jet in parsecs? (*Hint:* Use the small-angle formula, Chapter 3.)
4. Use the small-angle formula to find the linear diameter of a radio source with an angular diameter of 0.0015 arc second and a distance of 3.25 Mpc.

- If the active core of a galaxy contains a black hole of 10^6 solar masses, what will the orbital period be for matter orbiting the black hole at a distance of 0.33 AU? (*Hint*: See circular velocity in Chapter 5.)
- If a quasar is 1000 times more luminous than an entire galaxy, what is the absolute magnitude of such a quasar? (*Hint*: The absolute magnitude of a bright galaxy is about -21 .)
- If the quasar in Problem 6 were located at the center of our galaxy, what would its apparent magnitude be? (*Hints*: Use the magnitude-distance formula and ignore dimming by dust clouds.)
- Re-calculate Problem 7 assuming 30 magnitudes of extinction at visual wavelengths between Earth and the center of the Milky Way Galaxy.
- If the Hubble constant is 70 km/s/Mpc and a quasar has an apparent velocity of recession of 45,000 km/s, how far away is it?
- The hydrogen Balmer line H_{β} has a wavelength of 486.1 nm. It is shifted to 563.9 nm in the spectrum of 3C 273. What is the redshift of this quasar? (*Hint*: What is $\Delta\lambda$?)

Learning to Look

- The image at right combines visual (blue) with radio (red) to show the galaxy radio astronomers call Fornax A. Explain the features of this image. Is it significant that the object is a distorted elliptical galaxy in a cluster?



NRAO/AUI

- Explain the features of this radio image of the galaxy IC 708.

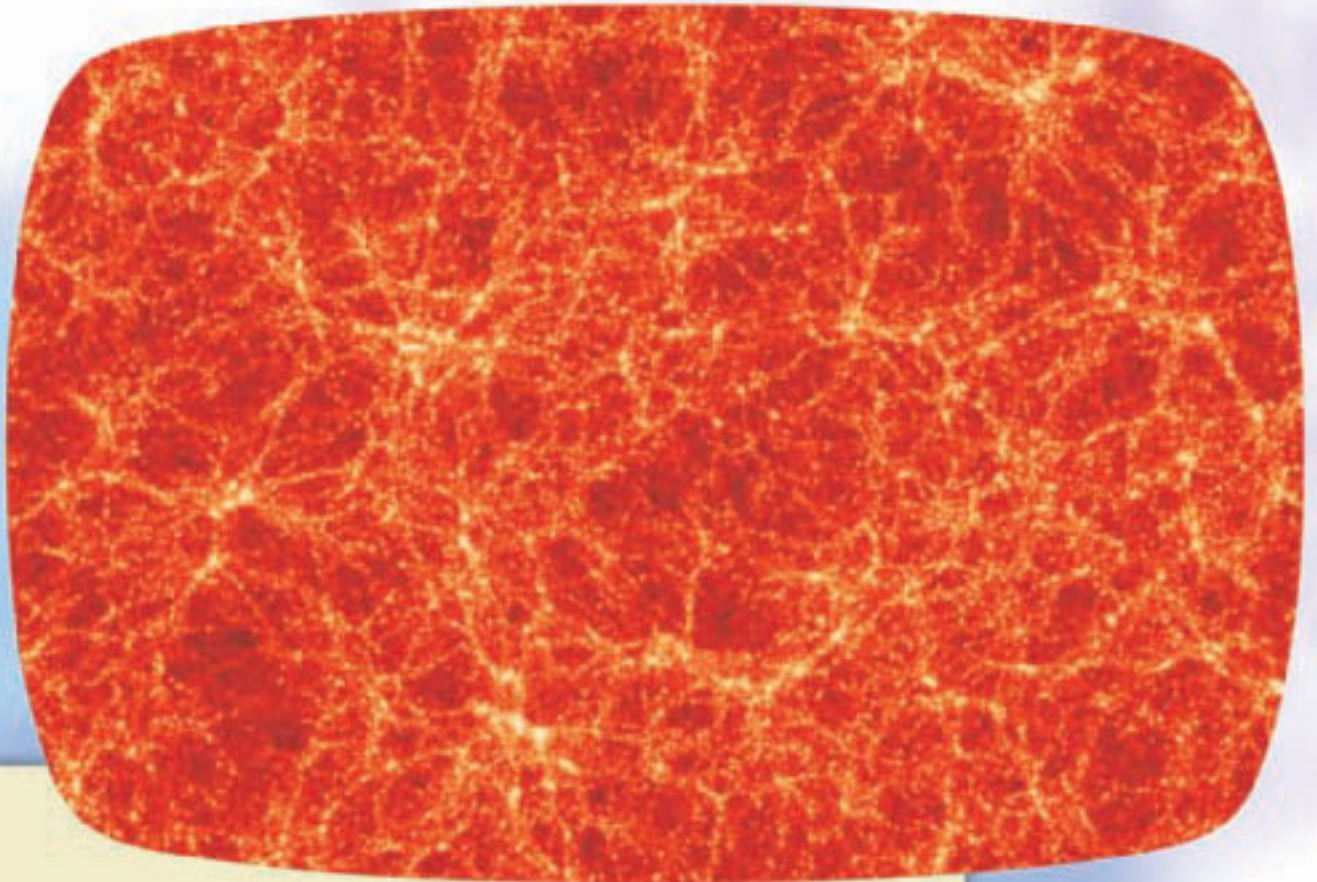


NRAO/AUI

- A radio image of quasar 3C 334 is shown at the right. There are two jets, so why do you see only one? What does it mean that this looks so much like a radio image of a double-lobed radio galaxy?



NRAO/AUI



Guidepost

Since Chapter 1, you have been on an outward journey through the universe. Now you have reached the limit of your travels in space and time and can study the universe as a whole. The ideas in this chapter are among the biggest and most difficult in all of science. Can you imagine a limitless universe, or the first instant of time?

As you explore cosmology, you will find answers to three essential questions:

- **Does the universe have an edge and a center?**
- **How do you know that the universe began with a big bang?**
- **How has the universe evolved, and what will be its fate?**

Once you have finished this chapter, you will have a modern insight into the nature of the universe, as well as where you are and what you are. After that, with an understanding of the big picture, it will be time to focus back on how your local neighborhood, the solar system, fits in—the subject of the rest of this book.

All of the energy and matter in the universe, including the matter in your body, began in the big bang. In this computer model of the evolution of the universe soon after the big bang, matter is being drawn together to form great clouds of galaxies. (MPA and Jörg Colberg)

The Universe, as has been observed before, is an unsettlingly big place, a fact which for the sake of a quiet life most people tend to ignore.

— DOUGLAS ADAMS *THE RESTAURANT AT THE END OF THE UNIVERSE*

LOOK AT YOUR THUMB. The matter in your body was present in the fiery beginning of the universe. **Cosmology**, the study of the universe as a whole, can tell you where your matter came from, and it can tell you where your matter is going.

Cosmology is a mind-bendingly weird subject, and you can enjoy it for its strange ideas. It is fun to think about space stretching like a rubber sheet, invisible energy pushing the universe to expand faster and faster, and the origin of vast walls of galaxy clusters. Notice that this is better than speculation—it is all supported by evidence. Cosmology, however strange it may seem, is a serious and logical attempt to understand the structure and evolution of the entire universe.

This chapter will help you climb the cosmology pyramid (■ Figure 18-1) one step at a time. You already have some ideas about what the universe is like. Start with those ideas, test them against observations, and compare them with scientific theories. Step by step, you can build a modern understanding of cosmology. Each step in the pyramid is small, but it leads to some astonishing insights into how the universe works and how you came to be a part of it.



■ **Figure 18-1**

Climbing the cosmology pyramid step by step isn't very difficult, and it leads to some fascinating ideas about the origin and evolution of the universe.

18-1 Introduction to the Universe

MANY PEOPLE HAVE AN IMPRESSION of the universe as a vase sphere of space filled with stars and galaxies (■ Figure 18-2). As you begin exploring the real universe, you need to become aware of your assumptions so they do not mislead you. The first step is to deal with an assumption so obvious that most people don't think about it, for the sake of a quiet life.

The Edge–Center Problem

In your daily life you are accustomed to boundaries. Rooms have walls, athletic fields have boundary lines, countries have borders, oceans have shores. It is natural to think of the universe also as having an edge, but that idea can't be right.

If the universe had an edge, imagine going to that edge. What would you find there: A wall of some type? A great empty space? Nothing? Even a child can ask: If there is an edge to the universe, what's beyond it? A true edge would have to be more than just an end of the distribution of matter. It would have to be an end of space itself. But, then, what would happen if you tried to reach past, or move past, that edge?

An edge to the universe violates common sense, and modern observations (which you will study later in this chapter) indicate that the universe could be infinite and would therefore have no



■ **Figure 18-2**

The entire sky is filled with galaxies. Some lie in clusters of thousands, and others are isolated in nearly empty voids between the clusters. In this image of a typical spot on the sky, the brightest objects are nearby stars; their "spikes" are caused by diffraction in the telescope. All other objects are galaxies ranging from the relatively close face-on spiral at upper right to the most distant galaxies visible only in the infrared, shown as red in this composite image. (R. Williams, STScI HDF-South Team, NASA)

edge. Perhaps even more important, if the universe has no edge, then it cannot have a center. You find the centers of things—pizzas, football fields, oceans, galaxies—by referring to their edges. If the universe has no edge, then it cannot have a center.

It is a **Common Misconception** to imagine that the universe has a center, but, as you just realized, that is impossible. As you study cosmology, you should take care to avoid thinking that there is a center of the universe.

The Idea of a Beginning

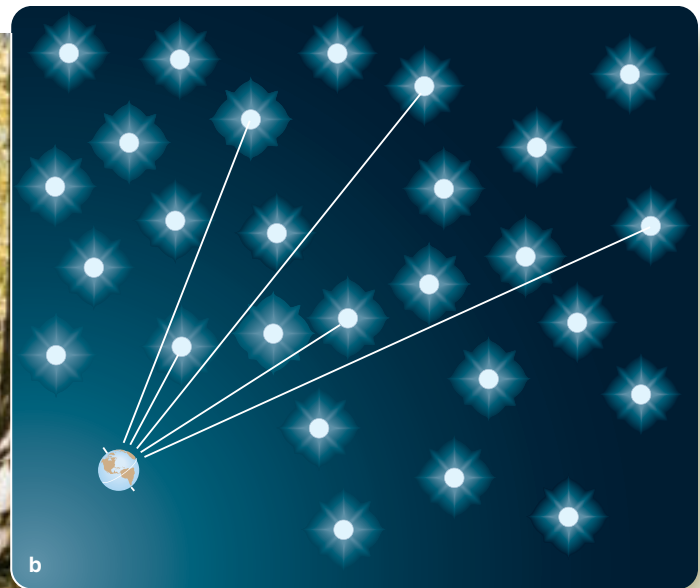
Of course you have noticed that the night sky is dark. That is an important observation because, you may be surprised to learn, seemingly reasonable assumptions about the universe can lead to the conclusion that the night sky actually should glow blindingly bright. This conflict between observation and theory is called **Olbers's paradox** after Heinrich Olbers, a physician and astronomer who publicized the problem in 1826. (*Problem* or *question* might be more accurate words than *paradox*.) Olbers was not the first person to pose this question; the problem of the dark night sky was first discussed by Thomas Digges in 1576 and was further analyzed by astronomers such as Johannes Kepler in 1610 and Edmund Halley in 1721. Olbers gets the credit through an accident of scholarship on the part of modern scientists who were not aware of the earlier discussions.

The point made by Olbers seems simple. Suppose you assume, as did most scientists in Olbers's time, that the universe

is infinite in size, infinite in age, **static** (a fancy word for unchanging overall), and filled with stars. If you look in any direction, your line of sight must eventually run into the surface of a star. (The clumping of stars into galaxies and galaxies into clusters can be shown mathematically to make no difference.) Look at ■ Figure 18-3, which uses the analogy of lines of sight in a forest. (The use of analogies in science is discussed in **How Do We Know? 18-1**.) When you are deep in a forest, every line of sight ends at a tree trunk, and you cannot see out of the forest.

By analogy to the view from inside a forest, every line of sight from Earth into space should eventually end at the surface of a star. Of course, the more distant stars would be fainter than nearby stars because of the inverse square law. However, the farther you look into space, the larger the volume you are viewing and the more stars are included; the two effects cancel out. The result would be that the entire sky should be as bright as the surface of an average star—like suns crowded “shoulder to shoulder,” covering the sky from horizon to horizon. It should not get dark at night.

Astronomers and physicists who study cosmology, called **cosmologists**, now believe they understand why the sky is dark. Olbers's paradox makes an incorrect prediction because it is based on incorrect assumptions. The universe may be infinite in size, but it is neither infinitely old nor static. The essence of modern cosmologists' answer to Olbers's question was suggested first by Edgar Allan Poe in 1848. Poe proposed that the night sky is



■ **Figure 18-3**

(a) Every direction you look in a forest eventually reaches a tree trunk, and you cannot see out of the forest. (Photo courtesy Janet Seeds) (b) If the universe is infinite and filled with stars, then any line from Earth should eventually reach the surface of a star. This assumption leads to a prediction that the night sky should glow as brightly as the surface of the average star, a puzzle commonly referred to as Olbers's paradox.

Reasoning by Analogy

How do scientists use analogies? “The economy is overheating, and it may seize up,” an economist might say. Economists like to talk in analogies because economics is often abstract, and one of the best ways to think about abstract problems is to find a more approachable analogy. Rather than discussing details of the national economy, you might be able to make conclusions about how the economy works by thinking about how a gasoline engine works.

Much of astronomy is abstract, and cosmology is the most abstract subject in astronomy. Furthermore, cosmology is highly mathematical, and unless you are prepared to learn some difficult mathematics, you instead have to use analogies, such as lines of sight in a forest.

Reasoning by analogy is a powerful technique. An analogy can reveal unexpected insights and lead you to further discoveries.

Carrying an analogy too far, however, can be misleading. You might compare the human brain to a computer, and that would help you understand how data flow in and are processed and how new data flow out, but the analogy is flawed. For example, although data in computers are stored in specific locations, memories are stored in the brain in a distributed form. No single brain cell holds a specific memory. So, if you carry the analogy too far, it can mislead you. Whenever you reason using analogies, you should be alert for their limitations.

As you study any science, be alert for analogies. They are tremendously helpful, but you have to be careful not to carry them too far.

The analogy between a human brain and a computer is of only limited use. (Blend Images/SuperStock)



dark because the universe is not infinitely old but came into existence at some finite time in the past. The more distant stars are so far away that light from them has not yet reached Earth. That is, if you look far enough away, the look-back time approaches the age of the universe, and you see to a time before the first stars began to shine. The night sky is dark because the universe had a beginning. You can now answer Olbers’s question, and understand why the night sky is dark, by revising your original assumptions about the universe.

The answer to Olbers’s question is a powerful idea because it clearly illustrates the difference between the universe and the **observable universe**. The universe is everything that exists, and it could be infinite. The observable universe, in contrast, is the part (maybe a very small part) that you can see from Earth using the most powerful telescopes. You will learn later in this chapter about evidence that the universe is around 14 billion years old. That means you can’t observe objects farther away than a look-back time of around 14 billion years. Do not confuse the observable universe, which is huge but finite, with the universe as a whole, which might be infinite.

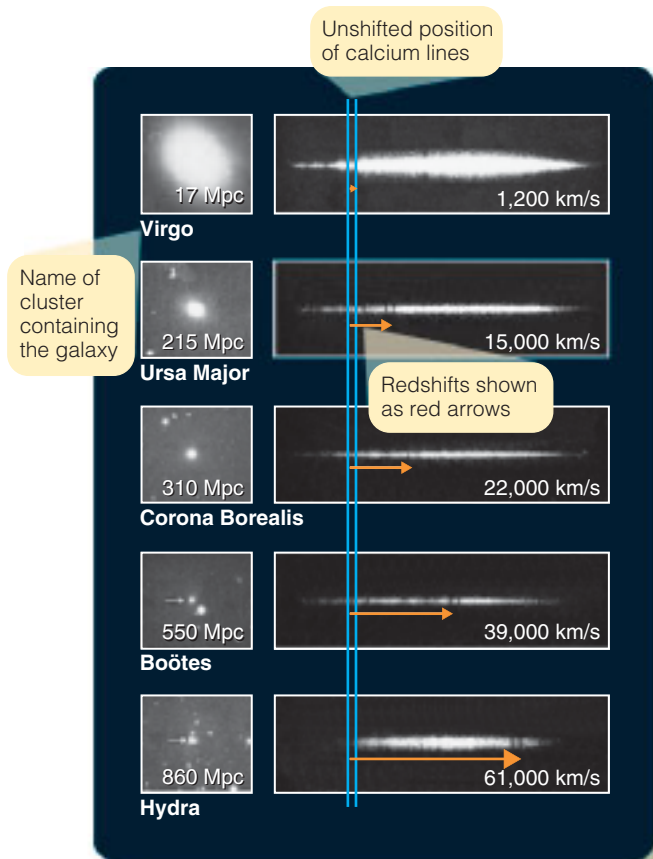
There is a **Common Misconception** that the universe is unchanging overall and not evolving. In the next section you will discover that the universe is actually changing. Observations reveal an **expanding universe**.

Cosmic Expansion

In 1929, Edwin Hubble published his discovery that the sizes of galaxy redshifts are proportional to galaxy distances. Nearby galaxies have small redshifts, and more distant galaxies have large redshifts. You learned this as the Hubble law in Chapter 16, when you used it to estimate the distances to galaxies. Those galaxy redshifts imply that galaxies are receding from each other and that the universe is expanding.

■ Figure 18-4 shows spectra of galaxies in galaxy clusters at various distances. The Virgo cluster is relatively nearby, and its redshift is small. The Hydra cluster is very distant, and its redshift is so large that the two dark spectral lines formed by ionized calcium are shifted from near-ultraviolet wavelengths well into the visible part of the spectrum.

The expansion of the universe does not imply that Earth has a special location. To see why, look at ■ Figure 18-5, which shows an analogy to baking raisin bread. As the dough rises, it pushes the raisins away from each other at speeds that are proportional to distance. Two raisins that were originally close to each other are pushed apart slowly, but two raisins that were far apart, having more dough between them, are pushed apart faster. If bacterial astronomers lived on a raisin in the raisin bread, they could observe the redshifts of the other raisins and derive a bacterial



■ **Figure 18-4**

These galaxy spectra extend from the near-ultraviolet at left to the blue part of the visible spectrum at right. The two dark absorption lines of once-ionized calcium are prominent in the near-ultraviolet. The redshifts in galaxy spectra are expressed here as apparent velocities of recession. Note that the apparent velocity of recession is proportional to distance, which is known as the Hubble law. (Caltech)

Hubble law. They would conclude that their universe was expanding uniformly. It does not matter which raisin the bacterial astronomers lived on, they would get the same Hubble law—no raisin has a special viewpoint. Similarly, astronomers in any galaxy will see the same law of expansion—no galaxy has a special viewpoint.

When you look at Figure 18-5, you see the edge of the loaf of raisin bread, and you can identify a center to the loaf. The raisin bread analogy to the universe stops working when you consider the crust—the edge—of the bread. Remember that the universe cannot have an edge or a center, so there is no center to the expansion. The raisin bread analogy is useful but also imperfect.

18-2 The Big Bang Theory

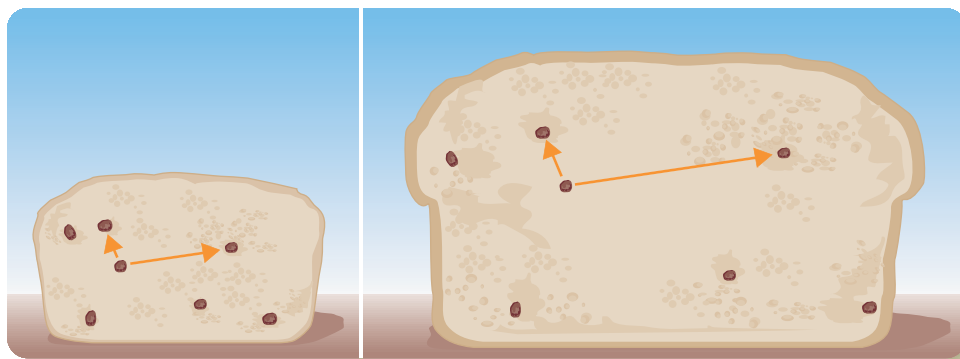
NOW YOU ARE READY to take a historic step up the cosmology pyramid. The expansion of the universe led cosmologists to conclude that the universe must have begun with an event of cosmic intensity.

Necessity of the Big Bang

Imagine that you have a video of the expanding universe and run it backward. You would see the galaxies getting closer to each other. There is no center to the expansion of the universe, so you would not see galaxies approaching a single spot. Rather, you would see the spaces between galaxies shrinking and the distances between all galaxies decreasing. Eventually, as your video ran back toward the beginning, galaxies would begin to merge. If you ran the video far enough back, you would see the matter and energy of the universe compressed into a high-density, high-temperature state. The expanding universe must have begun from this moment of extreme conditions that cosmologists call the **big bang**.

How long ago did the universe begin? You can estimate the age of the universe with a simple calculation. If you need to drive to a city 100 miles away, and you can travel 50 miles per hour, you divide distance by rate of travel and learn the travel time—in this example, 2 hours. In an analogous fashion, to find the age of the universe, you can divide the distance between two galaxies by the speed with which they are moving away from each other and find out how much time they have taken to reach their present separation.

The Hubble constant, H , has units km/s per Mpc, which is a velocity divided by a distance. This makes your task simple. If



■ **Figure 18-5**

An illustration of the raisin bread analogy for the expansion of the universe. As the dough rises, raisins are pushed apart with velocities proportional to distance. A colony of bacteria living on any raisin will find that the redshifts of the other raisins are proportional to their distances.

you calculate $1/H$, you have a distance divided by velocity, in other words, a time. To finish the division and get an age, you need to convert megaparsecs into kilometers, and then the distances will cancel out and leave you with an age in seconds. To convert seconds to years, you divide by the number of seconds in a year. If you make these simple changes in units, the age of the universe in years is approximately 10^{12} divided by H in its normal astronomical units, km/s/Mpc:

$$\tau_H = \frac{10^{12}}{H}$$

This estimate of the age of the universe is known as the **Hubble time**. For example, if H is 70 km/s/Mpc, that leads to an estimated age for the universe of $\frac{10^{12}}{70}$, or 14 billion, years. The time you calculate by this procedure is the same no matter which two galaxies you pick. You will fine-tune your estimate later in this chapter, but for the moment you can conclude that basic observations of the universe, especially the recession of the galaxies, require that the expansion of the universe began about 14 billion years ago.

The phrase *big bang* was invented by early critics of that theory, and the label gives a misimpression. Do not think of an edge or a center when you think of the big bang. It is a very **Common Misconception** that the big bang was an explosion and that the galaxies are flying away from the location of that explosion. Instead, try to imagine the entire universe. At the time of the big bang, all of the matter that now composes galaxies, stars, people, and atoms was much closer together. But, like the universe now, the early universe also had no center and no edge. The big bang filled the entire universe, happening everywhere at the same moment as the matter of the universe began to draw apart. A more accurate term than *big bang* might be *big stretch*.

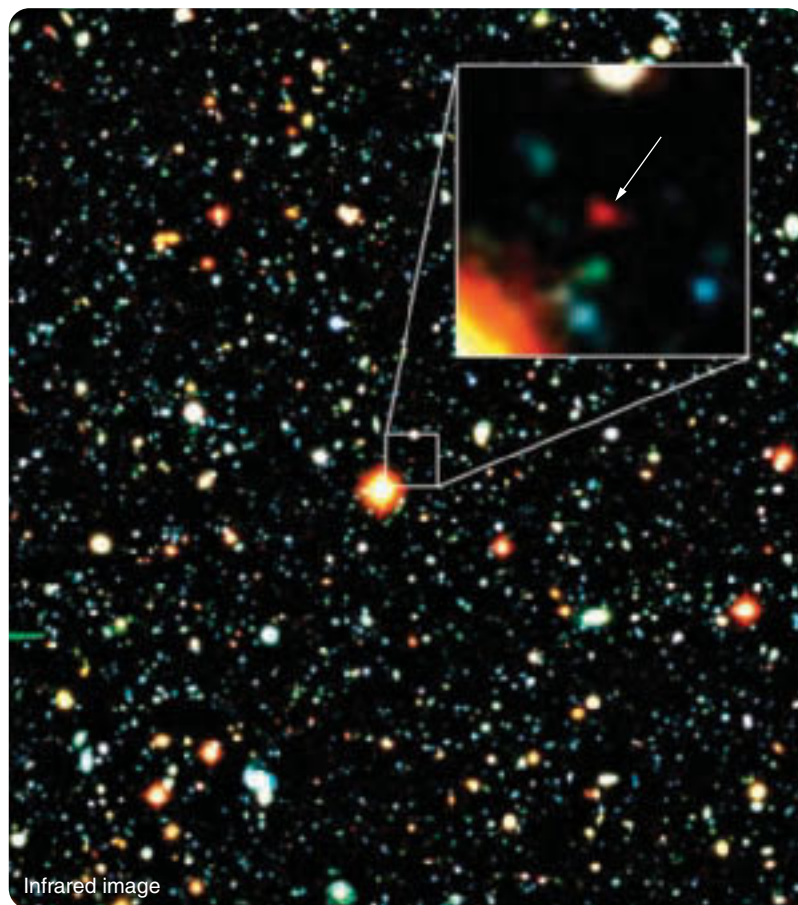
Although your imagination tries to visualize the big bang as a localized event, you should keep firmly in mind the correct picture that the big bang did not occur at a single place but filled the entire volume of the universe. The matter of which you are made was part of that big bang, so you are inside the remains of that event, and the universe continues to expand around you. You cannot point to any particular place and say, “The big bang occurred over there.” This is a brain-straining (stretching?) idea, but you will find

more information to help you understand it better later in this chapter when you study the nature of space and time.

Your instinct also is to think of the big bang as an event that happened long ago and can no longer be observed, like the Gettysburg Address. Amazingly, the effect of look-back time makes it possible to observe the big bang now, directly. The look-back time to nearby galaxies is “only” a few million years; the look-back time to more distant galaxies is a large fraction of the age of the universe (■ Figure 18-6).

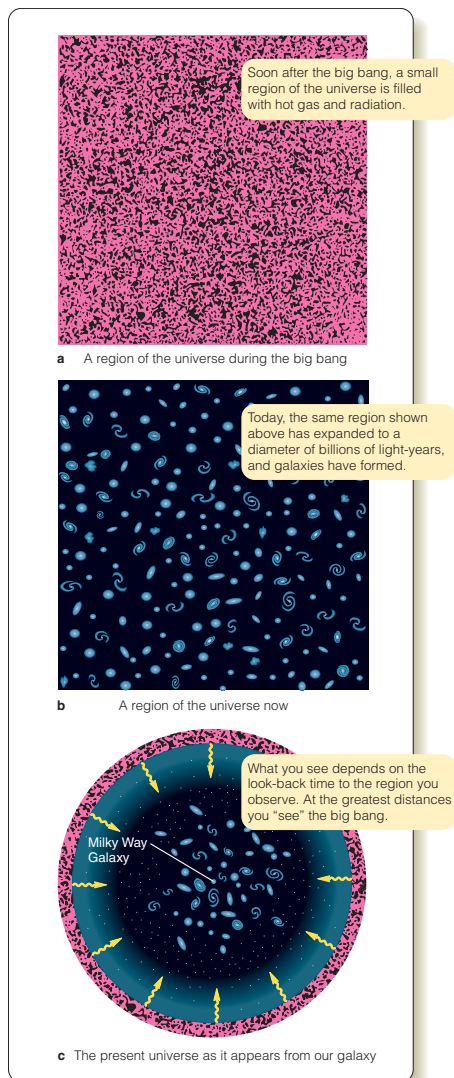
Suppose you look between the distant galaxies, seeing even farther away and farther back in time. You should be able to detect the hot gas that filled the universe long ago, right after the big bang, before the first stars and galaxies formed. The big bang occurred everywhere, and, in whatever direction you look, at great distance you can see back to the age when the universe was filled with hot gas (■ Figure 18-7).

The radiation that comes from such a great distance has a large redshift. The most distant visible objects are faint galaxies and quasars, with redshifts around 10. In contrast, the radiation from the hot gas right after the big bang has a redshift of about 1100. That means the light emitted as visible and near-infrared light by the hot gas in the early universe arrives at Earth as far-infrared, microwave, and radio waves. You can’t see it with your



■ **Figure 18-6**

This faint galaxy is one of the most distant ever found. It has a redshift of 6.964 implying that it is 12.88 billion light-years from Earth. It appears as it was only 850 million years after the big bang when the light began its journey toward Earth. (Subaru: Masanori Iye et al.)



■ **Figure 18-7**

This diagram shows schematically the expansion of a small part of the universe. Although the universe is now filled with galaxies, the look-back time distorts what you see. Nearby you see galaxies, but at greater distances, the look-back time reveals the universe at earlier stages, before galaxies formed. At very great distances, the big bang is detectable as infrared, microwave, and radio energy arriving from the hot gas that filled the universe soon after the big bang.

eyes, but it can be detected with infrared and radio telescopes. Unlike the Gettysburg Address, the big bang can still be observed by the radiation it emitted. That amazing discovery is the subject of the next section.

The Cosmic Background Radiation

The story of the discovery of radiation from the time of the big bang begins in the mid-1960s when two Bell Laboratories physicists, Arno Penzias and Robert Wilson, were measuring the

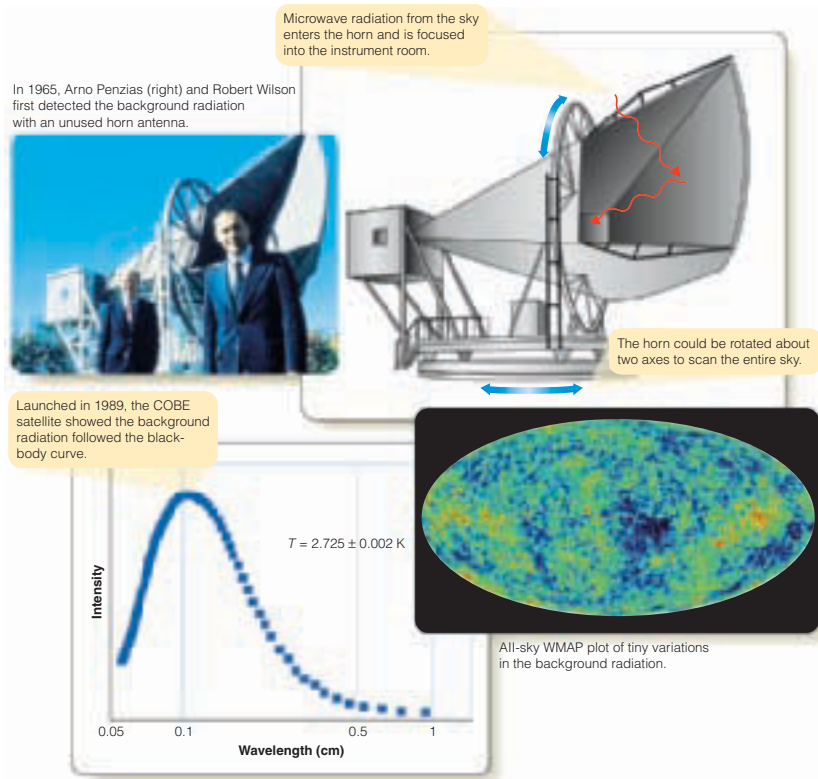
brightness of the sky at radio wavelengths (■ Figure 18-8). Their measurements showed a strange extra signal in the system, which they first attributed to the infrared glow from pigeon droppings inside the antenna. Perhaps they would have enjoyed scraping out the antenna more if they had known they would win the 1978 Nobel Prize in physics for the discovery they were about to make.

When the antenna was cleaned, they again measured the radio brightness of the sky and found the low-level noise was still there. The pigeons were innocent, but what was causing the extra signal?

The explanation for the noise goes back decades earlier. In 1939, astronomers noticed that spectra of some molecules in the interstellar medium showed they were bathed in radiation from a source with a temperature of 2 to 3 K. In 1948, physicist George Gamow predicted that the gases in the universe right after the big bang would have been hot and should have emitted strong blackbody radiation (see Chapter 7). A year later, physicists Ralph Alpher and Robert Herman pointed out that the large redshift of the big bang material relative to Earth would lengthen the wavelengths of that radiation into the microwave part of the spectrum, with a blackbody temperature they estimated as 5 K. In the mid-1960s Robert Dicke at Princeton concluded the radiation should be just strong enough to detect with newly developed techniques. Dicke and his team began building a receiver. When Penzias and Wilson heard of Dicke's work, they recognized the mysterious extra signal they had detected as radiation from the big bang, the **cosmic microwave background** radiation.

The detection of the background radiation was tremendously exciting, but cosmologists wanted confirmation. Theory predicted that the radiation should have a spectrum like blackbody radiation coming from a very cool source, but the critical observations could not be made from the ground because Earth's atmosphere is opaque at the predicted blackbody peak wavelength. It was not until 1990 that satellite measurements confirmed the background radiation has exactly a blackbody spectral distribution, with an apparent temperature of 2.725 ± 0.002 K—close to the original prediction.

It may seem strange that the gas of the big bang seems to have a temperature of just 2.7 degrees above absolute zero, but recall the tremendous redshift. Observers on Earth receive radiation that has a redshift of about 1100—that is, the wavelengths of the photons are about 1100 times longer than when they were emitted. The gas clouds that originally emitted the photons had a temperature of about 3000 K, and they emitted blackbody radiation with a λ_{max} of about 1000 nm (Wien's law, Chapter 7). Although that wavelength is in the near-infrared, the gas would also have emitted enough visible light to be seen glowing orange-red if there had been a human eye present at the time. The redshift has made the wavelengths of the background radiation about 1100 times longer on arrival at Earth than when they were



■ **Figure 18-8**

When the cosmic microwave background radiation was first detected in 1965, technology did not allow measurements at many wavelengths. Not until infrared detectors could be put in space was it conclusively shown that the background radiation has a blackbody spectrum, as predicted by theory. (Photo, AT&T Archives; WMAP plot, NASA)

emitted, so λ_{max} is now about 1 million nm, or 1 mm. That is why the hot gas of the big bang seems to be about 2.7 K, 1100 times cooler than it actually was.

The first few steps up the cosmology pyramid have not been very difficult. Simple observations of the darkness of the night sky and the redshifts of the galaxies tell you that the universe must have had a beginning, and you have seen that the cosmic microwave background radiation is clear evidence of the big bang, that the early universe was hot and dense. Theorists can combine these observations with modern physics to add some details to the story of how the big bang occurred.

Photon and Particle Soup

Cosmologists cannot begin their history of the big bang at time zero, because no one understands the physics of matter and energy under such extreme conditions, but they can come surprisingly close. If you could visit the universe when it was only 10 millionths of a second old, you would find it filled with high-energy photons having a temperature well over 1 trillion (10^{12}) K and a density of $5 \times 10^{18} \text{ kg/m}^3$, greater than the density of an atomic nucleus. (When cosmologists say the photons have a given temperature, they mean the photons have the same spectrum as blackbody radiation emitted by an object of that temperature.) Consequently, the photons in the early universe were gamma rays, with very short wavelength and therefore very high energy. (When cosmologists say that the radiation had a certain

density, they refer to Einstein's equation $E = mc^2$. Using that equation, you can express a given amount of radiation energy per volume as if it were matter of a certain density.)

If photons have enough energy, two photons can convert into a pair of particles—a particle of normal matter and a particle of **antimatter**. When an antimatter particle meets its matching particle of normal matter—when an antiproton meets a normal proton, for example—the two particles annihilate each other and convert their mass into energy in the form of two gamma rays. In the early universe, the photons were gamma rays and had enough energy to produce proton–antiproton pairs or neutron–antineutron pairs. When these particles collided with their antiparticles, they converted their mass back into photons. Thus, the early universe was filled with a dynamic soup of energy flickering from photons into particles and back again.

While all this went on, the expansion of the universe caused the temperature of the radiation to drop, reducing the energy of the photons. When the universe was 0.0001 second old, its temperature had fallen to 10^{12} K. By that time, the average energy of the radiation photons had fallen below the energy equivalent to the mass of a proton or a neutron, so the gamma rays could no longer produce such heavy particles. Those particles that did exist combined with their antiparticles and quickly converted their mass into energy.

It would seem that all of the protons and neutrons should have been annihilated with their antiparticles; but, for reasons that are poorly understood, a small excess of normal particles existed. For every billion protons annihilated by antiprotons, one survived with no antiparticle to destroy it. Consequently, you live in a world of normal matter, and antimatter is very rare.

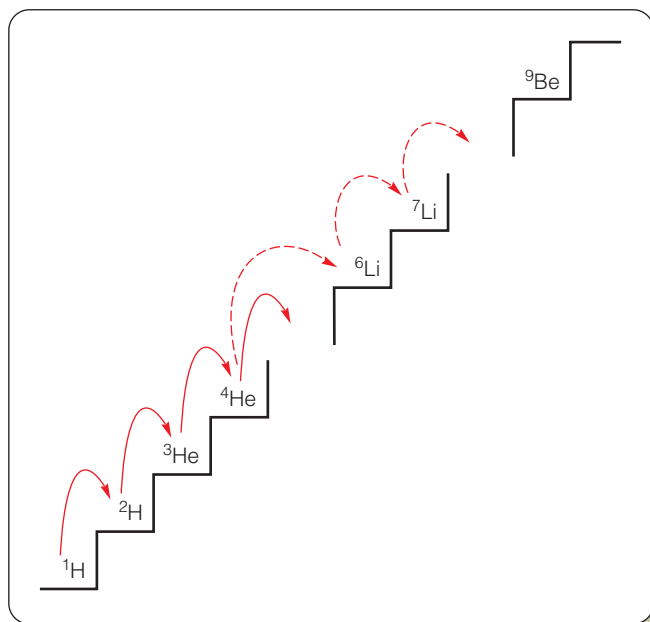
Although the gamma ray photons did not have enough energy when the universe was older than about 0.0001 second to produce any more protons and neutrons, they could still produce electrons and positrons (antielectrons; see Chapter 8), which are about 1800 times less massive than protons and neutrons. That process continued until the universe was about 1 minute old, at which time the expansion had cooled to the point at which there were no remaining photons with enough energy to create

electron–positron pairs. Again, most of the electrons and positrons combined to form photons, and only one in a billion electrons survived. Cosmologists can calculate, based on the known properties of subatomic particles and the characteristics of the universe as a whole, that the protons, neutrons, and electrons of which our universe is now made were produced during the first minute of its history.

A Few Minutes of Nucleosynthesis

The universal soup of hot gas and radiation continued to cool. Photons with high enough energy can break up an atomic nucleus, so the formation of stable nuclei could not occur until the universe had cooled enough. By the time the universe was about 2 minutes old, protons and neutrons could link to form deuterium, the nucleus of a heavy hydrogen atom, without being immediately broken apart. By the end of the third minute, further reactions began converting deuterium into helium.

Almost no atoms heavier than helium could be built in the big bang, because there are no stable nuclei with atomic weights of 5 or 8 (in units of the hydrogen atom). Nuclei of atomic weights 5 and 8 are radioactive and decay almost instantly back into smaller particles. Cosmic element building during the big bang had to proceed step by step, like someone hopping up a flight of stairs (■ Figure 18-9). The lack of stable nuclei at atomic



■ **Figure 18-9**

Cosmic element building. During the first few minutes of the big bang, temperatures and densities were high, and nuclear reactions built heavier elements. Because there are no stable nuclei with atomic weights of 5 or 8, the process built very few atoms heavier than helium.

weights of 5 and 8 meant there were missing steps in the stairway, and the step-by-step reactions had great difficulty jumping over these gaps during the few minutes of the big bang. As a result, cosmologists can calculate that only a tiny amount of lithium (atomic weight 7) would have been produced during the big bang, and no heavier elements.

By the time it was 3 minutes old, the universe had become so cool that almost all nuclear reactions had stopped. By the time it was 30 minutes old, the nuclear reactions had ended completely, and about 75 percent of the mass of the universe was in the form of protons—hydrogen nuclei. The rest was almost entirely helium nuclei. That composition, set during the first minutes of the universe, is the composition observed now for the oldest stars. Formation of elements with atomic weights greater than lithium had to wait for relatively slow-cooking nucleosynthesis processes in stars (see Chapters 12 and 13), beginning many millions of years after the big bang.

Radiation and Matter, Recombination and Reionization

After the era of nucleosynthesis, as the young universe continued to expand and cool, it went through a further sequence of four important changes. Originally, the universe was so hot that the gas was totally ionized, and the electrons were not attached to nuclei. The free electrons interacted with photons so easily that a photon could not travel very far before it encountered an electron and was deflected. The photons interacted continuously with the matter, and the radiation and matter cooled together at a rate set by the expansion rate of the universe. In those circumstances, the universe was dominated by its radiation.

The first change occurred when the universe reached an age calculated by cosmologists of about 50,000 years. Then, the density of energy in the form of photons became less than the density of the gas. Before that time, ordinary matter could not clump together because the intense sea of photons smoothed the gas out. As you will learn in the next section, dark matter, which does not interact with photons, was able to start clumping much earlier. After the 50,000-year mark, when the density of the universe's radiation permanently became less than that of its ordinary (baryonic) matter, ordinary matter could begin to draw together under the influence of the gravitational attraction of dark matter to form the clouds that eventually became galaxies.

The expansion of the universe spread the particles of the still-ionized gas farther and farther apart. When the universe reached an age of about 400,000 years, the second important change began. By then, the free electrons were spread so far apart that the photons could travel for thousands of parsecs before being deflected by an electron. In other words, the universe started to become transparent. At approximately the same time,

the third important change happened. As the falling temperature of the universe reached 3000 K, protons were able to capture and hold free electrons to form neutral hydrogen, a process called **recombination**. (This term is a little misleading, because the particles had never been together stably before; *combination* would be more accurate.) As the free electrons were gobbled up, the gas became essentially completely transparent, and the photons could travel through the gas without being deflected (■ Figure 18-10).

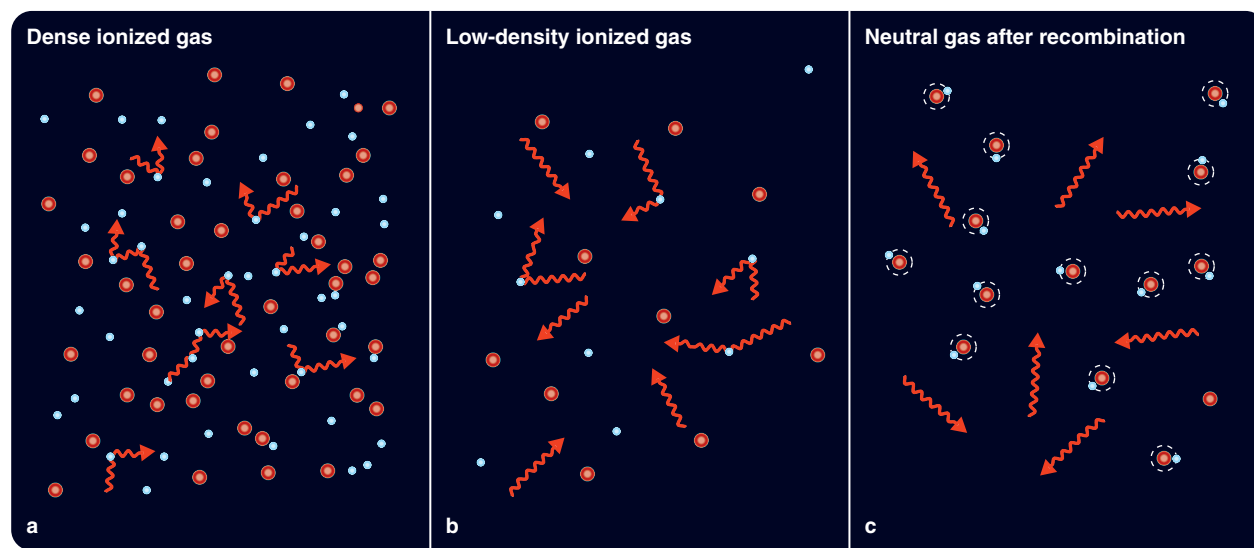
After recombination, although the gas continued to cool, the photons no longer interacted with the gas, and consequently the photons retained the blackbody temperature that the gas had at recombination. Those photons, which started their journey with a blackbody temperature of 3000 K, are observed now as the cosmic microwave background radiation. Remember that the large redshift—the expansion of the universe—has stretched the wavelengths of the background radiation so that it appears now to have a temperature of about 2.7 K.

After recombination, the gas that originated in the big bang was neutral, warm, and transparent. As the universe continued to expand and cool, the glow from the warm gas faded into infrared wavelengths. The universe entered what cosmologists call the **dark age**, a period lasting about 400 million years until the

formation of the first stars. During that interval the universe expanded in darkness.

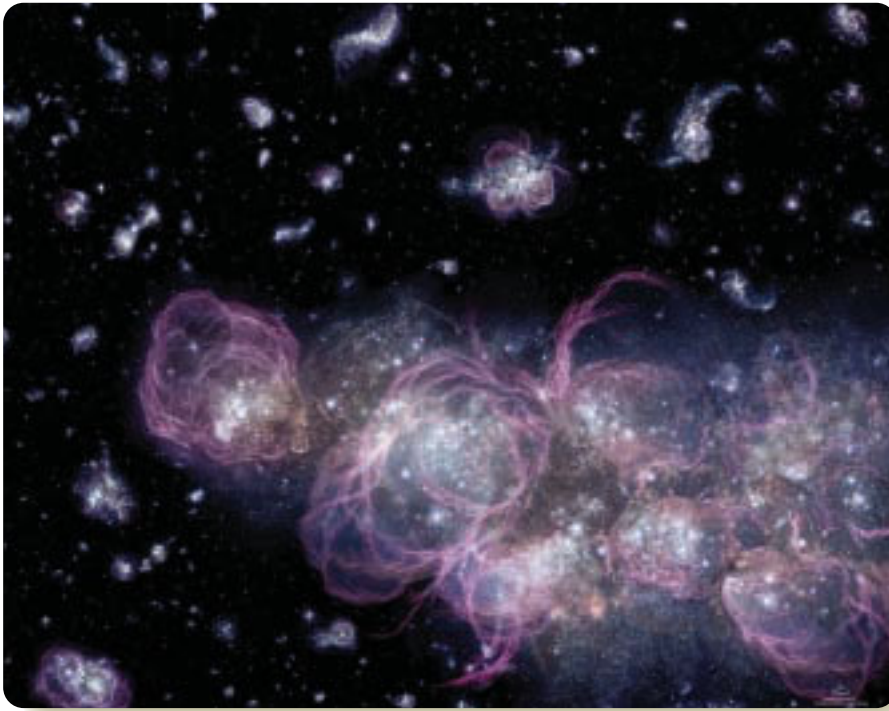
The fourth remarkable change happened as the first stars began to form, ending the dark age. The gas from which the first stars formed contained almost no metals and was therefore highly transparent. Mathematical models show that stars formed from this metal-poor gas would have been very massive, very luminous, and very short lived. That first violent burst of massive star formation produced enough ultraviolet light to begin ionizing the gas, and astronomers now, looking back to the most distant visible quasars and galaxies, can see traces of that **reionization** era in the universe (■ Figure 18-11). Reionization not only marked the end of the dark age, it was the beginning of the age of stars and galaxies in which you live now.

Look carefully at ■ Figure 18-12; it summarizes the story of the big bang, from the sorting out of stable particles in the earliest moments, through formation of helium in the first 3 minutes, up to the eras of energy–matter equality, recombination, and finally reionization of the gas. It may seem amazing that mere humans limited to Earth can draw such a diagram, but remember that it is based on evidence and on the best understanding of how matter and energy interact (**How Do We Know? 18-2**).



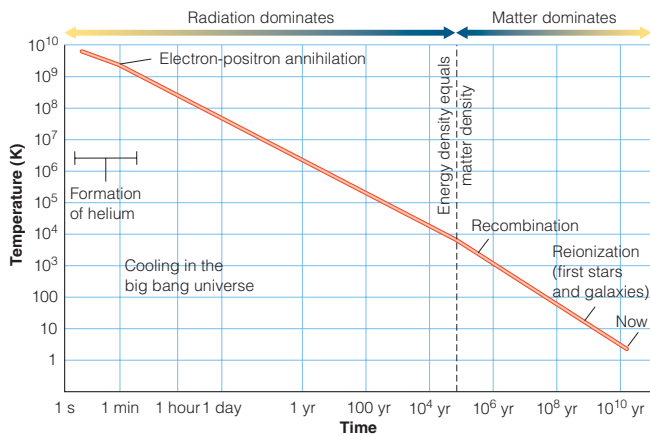
■ **Figure 18-10**

Photons scatter from electrons (blue) easily but hardly at all from the much more massive protons (red). (a) When the universe was very dense and ionized, photons could not travel very far before they scattered off an electron. This made the gas opaque. (b) As the universe expanded, the electrons were spread farther apart, and the photons could travel farther; this made the gas more transparent. (c) After recombination, most electrons were locked to protons to form neutral atoms, and the gas became highly transparent.



■ **Figure 18-11**

In this artist's conception of reionization, the first stars produce floods of ultraviolet photons that ionize the gas in expanding bubbles. Such a storm of star formation ended the dark age, during which the universe expanded in darkness. Spectra of the most distant quasars reveal that those first galaxies were surrounded by neutral gas that had not yet been fully ionized. Thus the look-back time allows modern astronomers to observe the age of reionization. (K. Lanzetta, SUNY, A. Schaller for STScI, and NASA)



■ **Figure 18-12**

During the first few minutes of the big bang, some hydrogen was fused to produce helium, but the universe quickly became too cool for such fusion reactions to continue. The rate of cooling increased as matter began to dominate over radiation. Recombination freed the radiation from the influence of the gas, and reionization was caused by the birth of the first stars. Note how the exponential scale in time stretches early history and compresses recent history.

SCIENTIFIC ARGUMENT

How do you know there was a big bang?

A good scientific argument combines evidence and theory to describe how nature works, and this question calls for a detailed argument. The cosmic microwave background radiation consists of photons emitted by warm gas after the big bang, so when astronomers detect those photons, they are in a sense “seeing” the big bang. Of course, all scientific evidence must be interpreted, so you need to understand how the big bang could produce radiation all around the sky before you can accept the background radiation as evidence. First, you must remember that the big bang event filled the entire universe with hot, dense gas. The big bang didn't happen in a single place; it happened everywhere. At recombination, the expansion of the universe reached the stage where the matter became transparent, and the

radiation that had previously been trapped, bouncing between matter particles, was freed to travel through space. Now, that radiation from the age of recombination arrives from all over the sky. It is all around you because you are part of the big bang event, and as you look out into space to great distance, you look back in time and see the hot gas in any direction you look. You can't see the radiation as visible light because the large redshift has lengthened the wavelengths by a factor of 1100 or so, but you can detect the radiation as photons with infrared, microwave, and radio wavelengths.

With this interpretation, the cosmic microwave background radiation is powerful evidence that there was a big bang. That tells you how the universe began, but your argument includes an important point. **Why do you think the universe cannot have a center or an edge?**

Science: A System of Knowledge

What is the difference between believing in the big bang and understanding it? If you ask a scientist, “Do you believe in the big bang?” she or he may hesitate before responding. The question implies something incorrect about the way science works.

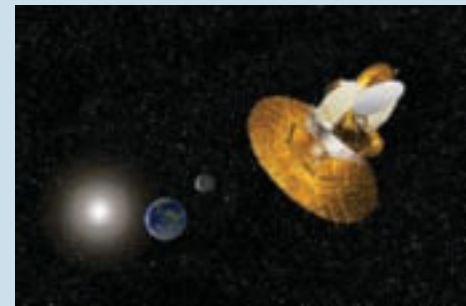
Science is a system of knowledge and process but does not operate as a system of belief. Science is an attempt to understand logically how nature works and is based on observations and experiments used to test and confirm hypotheses and theories. A scientist does not really believe in even a well-confirmed theory in the way people normally use the word *believe*. Rather, the scientist understands the theory and recognizes how different pieces of evidence support or contradict the theory.

There are other ways to know things, and there are many systems of belief. Religions, for example, are systems of belief that are not entirely based on observation. In some

cases, a political system is also a system of belief; many people believe that democracy is the best form of government and do not ask for, or expect, evidence supporting that belief. A system of belief can be powerful and lead to deep insights, but it is different from science.

Scientists try to be careful with words, so thoughtful scientists would not say they *believe* in the big bang. They would say that the evidence is overwhelming that the big bang really did occur and that they are compelled, by a logical analysis of both the observations and the theory, to conclude that the theory is very likely correct. In this way scientists try to be objective and reason without distortion by personal feelings and prejudices.

A scientist once referred to “the terrible rule of evidence.” Sometimes the evidence forces a scientist to a conclusion she or he does not like, but science is not a system of



Scientific knowledge is based objectively on evidence such as that gathered by spacecraft.
(NASA/WMAP Science Team)

belief, so the personal preferences of each scientist must take second place to the rule of evidence.

Do you believe in the big bang? Or, instead, do you have confidence that the theory is right because of your analysis of the evidence? There is a big difference.

18-3 Space and Time, Matter and Energy

HOW CAN THE BIG BANG have happened everywhere? To solve the puzzle, you need to put seemingly reasonable expectations aside and look carefully at how space and time behave on cosmic scales.

Looking at the Universe

The universe looks about the same in whichever direction you observe; in cosmologist language the universe is described as being **isotropic**. Of course, if you look toward a galaxy cluster you see more galaxies than in other directions, but that is only a local variation. On the average, you see similar numbers of galaxies in every direction. Furthermore, the background radiation is almost perfectly uniform across the sky. The universe is observed to be very isotropic.

The universe also seems about the same everywhere; in cosmologist language the universe is described as being **homogeneous**. (Note that this is a different property than the universe being isotropic.) Of course, there are local variations; some regions contain more galaxies and some less. Also, because the universe evolves, at large look-back times you see galaxies at an earlier developmental stage. But, if you account for those well-understood

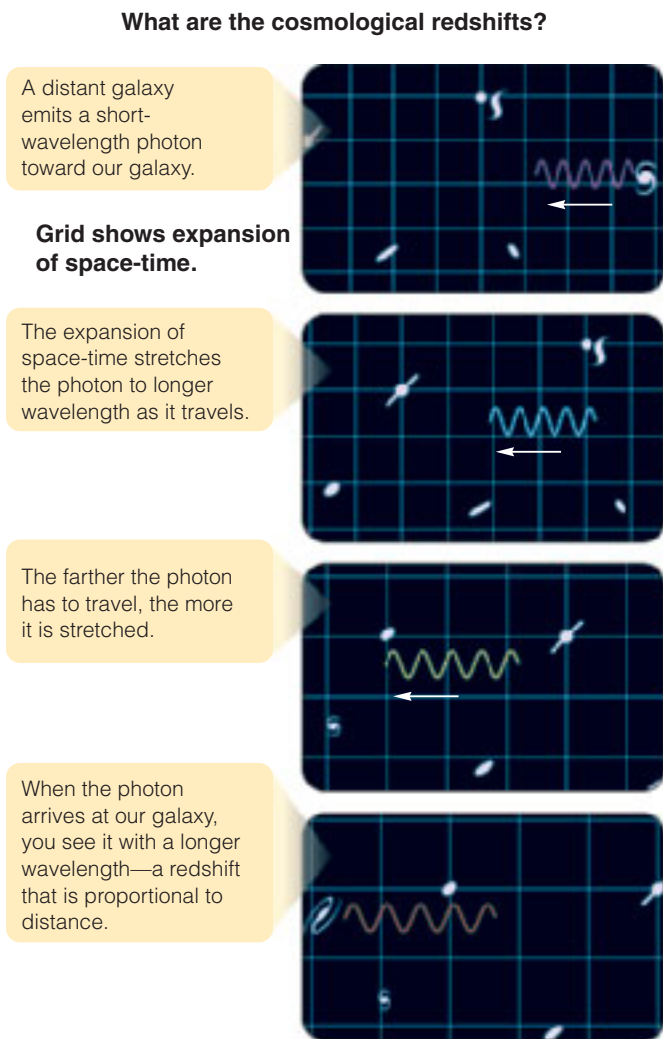
variations, then the universe seems to be, on average, the same everywhere.

The universe is observed to be isotropic and homogeneous. Those two properties don't have to go together; for an intellectual exercise, you can try to imagine arrangements that are isotropic but not homogeneous, or homogeneous but not isotropic. The fact that the universe is both isotropic and homogeneous leads to the **cosmological principle**, which says that any observer in any galaxy sees the same general properties for the universe. As you just learned, this overall principle intentionally overlooks minor local and evolutionary variations. The cosmological principle implies there are no special places in the universe. What you see from the Milky Way Galaxy is typical of what all intelligent creatures see from their respective home galaxies. Furthermore, the cosmological principle states, in a new form, the idea that the universe can have no center or edge. A center or an edge would be a special place, and the cosmological principle says there are no special places.

The Cosmic Redshift

Einstein's theory of general relativity, published in 1916, describes space and time together as the fabric of the universe, called space-time. That idea will give you a new insight into the meaning of the phrase *expanding universe*.

General relativity describes space-time as if it is made of stretching rubber, and that explains one of the most important observations in cosmology—the redshifts. It is a **Common Misconception** that cosmological redshifts are Doppler shifts of galaxies flying away through space. Instead, except for relatively small, local motions within clusters of galaxies, galaxies are at rest. They are being *separated* from each other as space-time expands. Also, as space-time expands, it stretches any photon traveling through space so that its wavelength increases. Photons from distant galaxies spend more time traveling through space and are stretched more, in other words have larger redshifts, than photons from nearby galaxies. That is why redshift depends on distance (■ Figure 18-13).



■ **Figure 18-13**

Like a rubber sheet, space-time stretches, moving the galaxies away from each other and increasing the wavelength of photons as they travel through space-time.

Astronomers often express redshifts as if they were actual radial velocities, but the redshifts of the galaxies are not Doppler shifts. That is why this book is careful to refer to a galaxy's *apparent* velocity of recession. Some textbooks convert cosmological redshifts to velocities using Einstein's relativistic Doppler formula, but that formula applies to motion through space and not to the behavior of space-time itself, so that formula should not be used in a cosmological context. The Hubble law still applies: Redshifts can be used to find the distance to galaxies because redshifts show how much the universe has expanded, and thus how much time has elapsed, since the photons started on their journey.

Model Universes

Almost immediately after Einstein published his general relativity theory, other theorists were able to solve the sophisticated mathematics and compute simplified descriptions of the behavior of space-time and matter. The resulting model universes dominated cosmology throughout the 20th century.

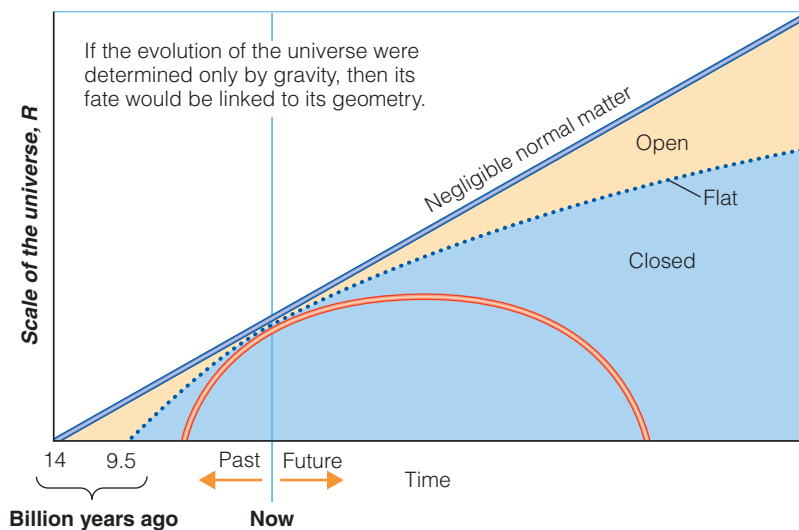
The equations allowed three possibilities. Space-time might be curved in either of two different ways, or it might have no curvature at all. Most people find these curved models difficult to imagine, and modern observations have shown that the simplest model, without curvature, is almost certainly correct, so you don't have to wrap your brain around the curved models. You might, however, like to know a few of their most important properties.

Some models described space-time as being curved back on itself to form a **closed universe**. You would not notice this curvature in daily life; it would only be evident in measurements involving very distant objects. Throughout the 20th century, observations could not eliminate closed models, so they were considered a real possibility. Closed universe models have finite volumes, but, because space-time is curved back on itself, a closed universe nevertheless would have no edge and no center. Such closed models predicted that the expansion of the universe would eventually become a contraction that would bring all of the matter and energy back to the high-density big bang state, which was sometimes called the "big crunch."

Other models described an uncurved, **flat universe**. That is the kind of space-time you would expect from your daily life, with the same rules of geometry that you learned in high school, even for cosmological distances. Flat models are infinite, have no edge or center, and expand forever.

A third kind of model described an **open universe**. Such models contain curved space-time but are not curved back on themselves. Like the flat models, open models are infinite, have no center or edge, and expand forever.

Cosmologists of the 20th century struggled to find reasons or observations that would allow them to choose among these three kinds of models. The main clue was density. According to general relativity, the overall curvature of space-time is



■ **Figure 18-14**

Illustrations of some simple universe models that depend only on the effect of gravity, without including dark energy. Open universe models expand without end, and the corresponding curves fall in the region shaded orange. Closed models expand and then contract again (red curve, one example). A flat universe (dotted line) marks the boundary between open and closed universe models. The relationship between estimated age and actual age of the universe depends on the curvature of space-time in universe models without dark energy. The age of the universe for each model is shown on the graph as the horizontal distance from “Now” back to the time when the universe scale factor R equaled 0.

determined by the average density of matter plus energy in the universe. Cosmologists could calculate that space-time is flat if the average density of the universe equals a **critical density** of $9 \times 10^{-27} \text{ kg/m}^3$. If the average density of the universe is more than the critical density, the universe must be closed; and if it is less, the universe must be open. Attempts to measure the actual value of the universe’s density, however, were difficult and inconclusive.

These three kinds of universe models are illustrated in ■ Figure 18-14, which compares the expansions versus time of the different models. The parameter R on the vertical axis is a measure of the extent to which the universe has expanded. You can think of R , in a simplified way, as the average distance between galaxies. In the figure you can see that closed universes expand and then contract while both flat and open universes expand forever.

Notice that you can’t find the actual age of the universe unless you know whether it is open, closed, or flat. The Hubble time is the age the universe would have if it were totally open, which would mean it contained almost no matter. If, instead, the universe is dense enough to have flat geometry, then its age would be $\frac{2}{3}$ of the Hubble time. If H is about 70 km/sec/Mpc , as astronomers have measured, and the universe is flat, then it

should be only 9.5 billion years old. Astronomers know of globular star clusters that are significantly older than that, so this was known as the age problem: How can the universe be younger than some of the objects in it?

Modern observations show that the universe is flat, and later in this chapter you will see how the evidence eliminated curved models and solved the age problem. For now, however, you can think about a different puzzle. If the universe is flat, then its average density must exactly equal the critical density. Yet when cosmologists added up the matter that could be detected, they found only a few percent of the critical density. They wondered if the dark matter made up the rest.

Dark Matter in Cosmology

There is more to the universe than meets the eye. In Chapters 15 and 16, you discovered that the Milky Way Galaxy and other galaxies have much stronger gravitational fields than would be predicted based on the amount of stars visible. Their gravitational fields are much stronger than expected even when you add in the gravity of the gas and dust that would be contained in the galaxies. Galaxies must contain dark matter.

This is not a small issue. Look at ■ Figure 18-15. Gravitational lensing is dramatic evidence of dark matter. The galaxy cluster in the figure contains so much dark matter that it warps space-time and focuses the images of more distant galaxies into short arcs of light. The universe contains much more dark matter than normal matter. Looking at the universe of visible matter in galaxies is like looking at a tree and seeing only the leaves.

The available evidence shows that dark matter is not the same as the normal matter you are made of. To follow that argument, you need to estimate the density of normal matter, and you can start with what is known about conditions right after the big bang.

As you have learned, during the first few minutes of the big bang, nuclear reactions converted some protons into helium and a very small amount into other elements. How much of elements heavier than helium could be produced was controlled by the density of normal matter during the big bang. For example, if the density of matter had been high so that there were lots of normal particles such as protons and neutrons flying around, they would have collided with the deuterium nuclei and converted most of them into helium. On the other hand, if the density of normal particles had been relatively low, more deuterium would have survived intact without being converted to helium.

Figure 18-9 shows that there is a gap between helium and lithium; there is no stable nucleus with atomic mass 5, so regular nuclear reactions during the first few minutes of the big bang had difficulty converting helium into lithium. If, however, the density of protons and neutrons was high enough, a few nuclear reactions could have leaped the gap and produced a small amount of the isotope lithium-7.



■ **Figure 18-15**

Gravitational lensing shows that galaxy clusters contain much more mass than what is visible. The yellowish galaxies in this image are members of a relatively nearby cluster of galaxies. Most of the objects in this image are blue or red images of very distant galaxies focused by the gravitational field of the cluster. Some of these imaged galaxies may be over 13 billion light-years away. That they can be seen at all is evidence that the foreground galaxy cluster contains large amounts of dark matter. (NASA, Benites, Broadhurst, Ford, Clampin, Hartig, Illingworth, ACS Science Team and ESA)

Both deuterium and lithium are destroyed in stars, so astronomers have attempted the difficult task of studying clouds of gas at large look-back times that had not yet been altered by nuclear reactions in stars. As shown in ■ Figure 18-16, the amount of deuterium observed now in the universe sets a lower limit on the density of the universe relative to the critical density, and the observed abundance of lithium-7 sets an upper limit. The surprising conclusion from these observations and calculations is that normal matter from which you, Earth, and the stars are made cannot make up more than 5 percent of the critical density. Yet observations of gravitational effects show that galaxies and galaxy clusters contain much larger amounts of matter than that, which can't be normal matter but instead must be dark matter.

The protons and neutrons that make up normal matter belong to a family of subatomic particles called *baryons*, so

cosmologists believe that most of the dark matter cannot be baryons. Only a few percent of the mass in the universe can be ordinary baryonic matter; the dark matter must be **nonbaryonic** matter.

Some theorists thought that neutrinos, particles that are predicted to be very abundant in the universe yet are not baryons, might have enough mass to make up the dark matter, but modern measurements show that neutrinos are not massive enough. Some particle physics theories predict the existence of a new type of particle that are labeled **WIMPs** (weakly interacting massive particles), but they have not been detected with certainty in the laboratory. The true nature of dark matter remains one of the major mysteries of astronomy.

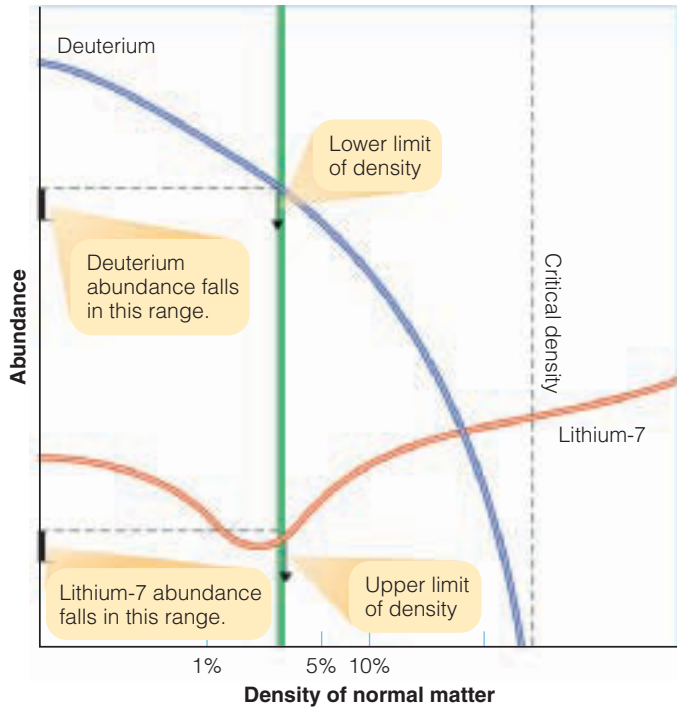
Theoretical models of galaxy formation in the early universe provide more hints about the nature of dark matter. If dark matter is composed of particles that were moving at, or near, the speed of light

when matter and energy had equal density, that is referred to as **hot dark matter**. Such fast-moving particles do not clump together easily and could not have stimulated the formation of objects as small as galaxies and clusters of galaxies. Instead, the most successful models of galaxy formation require that the dark matter is actually made up of **cold dark matter**, meaning the particles move slowly and can clump into relatively small structures.

Nonbaryonic dark matter does not interact significantly with normal matter or with photons, which is why you can't see it. This also means that dark matter was not affected by the intense radiation that dominated the universe when it was very young. So long as radiation dominated the universe, it prevented clouds of normal matter from contracting to begin forming galaxies. But the dark matter was immune to the radiation, and the dark matter could contract to form clumps while the universe was very young. In other words, dark matter could have given galaxy formation a head start soon after the big bang. Models with cold, nonbaryonic dark matter are most successful at predicting the formation of galaxies and clusters of galaxies with the right size and at the right time in the history of the universe to match the observations.

Although the evidence is very strong that plenty of dark matter exists, it is still not abundant enough to make the universe flat. Dark matter constitutes less than 30 percent of the critical density. As you will see later in this chapter, there is more to the universe than meets the eye, more even than dark matter.

18-4 21st-Century Cosmology



■ **Figure 18-16**

This diagram compares observation with theory. Theory predicts how much deuterium (blue curve) and lithium-7 (red curve) you would observe for different densities of normal matter. The observed density of deuterium falls in a narrow range shown at upper left and sets a lower limit on the possible density of normal matter. The observed density of lithium-7, shown at lower left, sets an upper limit. This means the true density of normal matter must fall in a narrow range represented by the green column. Certainly, the density of normal matter is much less than the critical density.

SCIENTIFIC ARGUMENT

Why do cosmologists think that dark matter can't be baryonic?

Good scientific arguments always fall back on evidence. In this case the evidence is very compelling. Small amounts of isotopes like deuterium and lithium-7 were produced by nuclear reactions in the first minutes of the big bang, and the resulting abundance of those elements depends strongly on how many protons and neutrons were available at that time. Because those particles belong to the family of particles called baryons, physicists refer to normal matter as baryonic. Measurement of the abundances of deuterium and lithium-7 show that the universe cannot contain more baryons than about 5 percent of the critical density. Yet, observations of galaxies and galaxy clusters show that dark matter must make up almost 30 percent of the critical density. Consequently, cosmologists conclude that the dark matter must be made up of nonbaryonic particles.

Finding the dark matter is important because the density of matter in the universe determines the curvature of space-time. Now build a new argument. **How does the modern understanding of space-time explain cosmic redshifts?**

IF YOU ARE A LITTLE DIZZY from the weirdness of expanding space-time and dark matter, make sure you are sitting down before you read further. As the 21st century began, astronomers made a discovery that startled all cosmologists: The expansion of the universe is actually accelerating. You'll have to go back a couple of decades to understand how that amazing new discovery nevertheless fits well with some of the things you have learned already in this chapter.

Inflation

By 1980, accumulating evidence had made the big bang theory widely accepted by cosmologists, but it faced two problems that led to the development of a new theory—a revised big bang with an important addition.

One of the problems is called the **flatness problem**. The properties of the universe appear to be close to the dividing line between being open or closed; that is, the geometry of the universe seems nearly flat, and therefore its density is close to the critical density. Given the vast range of possibilities, from zero to infinity, it seems peculiar that the density of the universe is close to the critical value. If dark matter is as common as the measurements indicate, the universe's density must be within a factor of three of the critical density.

Even a small departure from critical density when the universe was young would be magnified by subsequent expansion. To be so near critical density now, the density of the universe during its first moments must have been within 1 part in 10^{49} of the critical density. So the flatness problem can be stated as: Why is the universe so close to perfectly flat?

The second problem with the original big bang theory is called the **horizon problem**. This is related to the observed isotropy of the cosmic microwave background radiation. When astronomers make a correction for the motion of Earth, they see the same intensity and temperature of background radiation in all directions to a precision of better than 1 part in 1000. Yet when you observe background radiation coming from two points in the sky separated by an angle larger than about 1 degree, you are looking at two bits of matter that seemingly should never have been connected from the time of the big bang up to the time when the radiation was emitted. In other words, when recombination occurred and the gas of the big bang became transparent to the background radiation, the universe was not old enough for any form of energy to have traveled from one of those two regions to the other. Thus, according to the standard big bang theory, the two spots you observe had not had enough time, since the start of the big bang, to exchange energy and equalize their temperatures. (The term *horizon* is used in this context because the two spots are said to lie beyond their

respective light-travel horizons.) Then, how did every part of the entire big bang universe get to be so nearly the same temperature at the time of recombination?

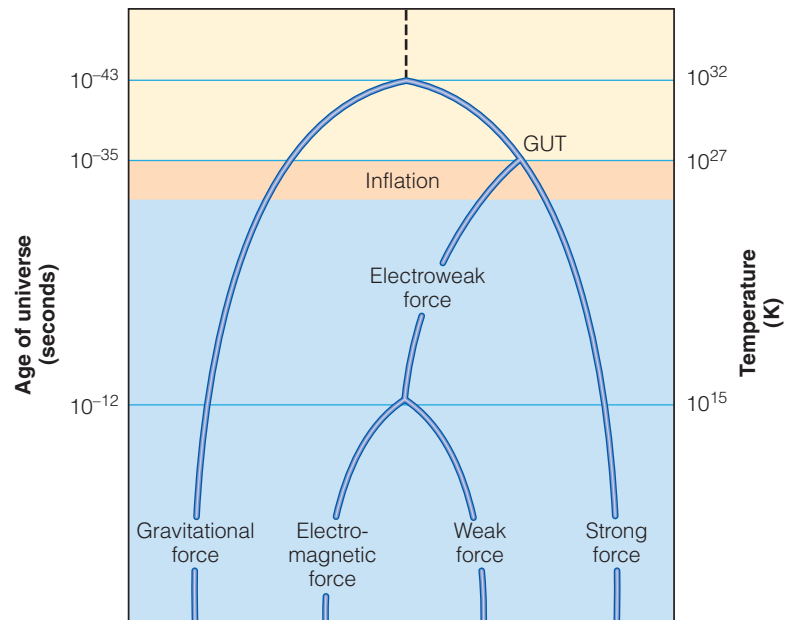
The key to these two problems and to others involving subatomic physics may lie with the hypothesis called the **inflationary universe**. That hypothesis predicts there was a sudden enormous expansion called *inflation* when the universe was very young, even more extreme than that predicted by the original big bang theory.

To understand the inflationary universe, you need to recall that physicists know of only four forces—gravity, the electromagnetic force, the strong force, and the weak force (see Chapter 8). You are familiar with gravity; you fought it to get out of bed this morning. The electromagnetic force is responsible for making magnets stick to refrigerator doors and cat hair stick to sweaters charged with static electricity, as well as holding electrons in orbit around atomic nuclei and being intimately connected with processes that make light and radiation. The strong force holds atomic nuclei together, and the weak force is involved in certain kinds of radioactive decay.

For many years, theorists have tried to unify these forces; that is, they have tried to describe all four forces as aspects of a single mathematical law. A century ago, James Clerk Maxwell showed that the electric force and the magnetic force were really the same effect, and physicists now count them as a single electromagnetic force. Similarly, in the 1960s, theorists succeeded in unifying the electromagnetic force and the weak force in what is now called the electroweak force. Those two forces operate effectively as a single unified force, but only in very high-energy processes. At lower energies the electromagnetic force and the weak force behave differently. Now, theorists have proposed ways of unifying the electroweak force with the strong force at even higher energies. These new theories are called **grand unified theories, or GUTs**.

According to the inflationary universe hypothesis, the universe expanded and cooled until about 10^{-36} seconds after the big bang, when it became cool enough that the electroweak force and the strong force began to disconnect from each other; that is, they began to behave in different ways (■ Figure 18-17). Cosmologists calculate that this change would have released tremendous energy, which then suddenly inflated the universe by a size factor of 10^{50} or larger. At the start of inflation, the part of the universe that is now observable from Earth is estimated to have been 35 orders of magnitude smaller than a proton, but it suddenly inflated to roughly a meter across and then continued its slower expansion to its present extent.

Early rapid inflation of the universe can solve both the flatness problem and the horizon problem. The sudden inflation of the universe would have forced whatever curvature it had before that moment toward a value of zero, just as inflating a balloon makes regions on its surface flatter. Consequently, you now live



■ **Figure 18-17**

When the universe was very young and hot (top), the four forces of nature were indistinguishable in behavior. As the universe began to expand and cool, the forces “separated,” meaning that they began to have different characteristics, which released a huge amount of energy and triggered a sudden rapid inflation in the size of the universe.

in a universe that is almost perfectly flat because of that long-ago moment of inflation. In addition, because what is now the entire observable part of the universe was only about 10^{-59} light seconds across when the universe was about 10^{-36} seconds old, it would have had enough time to equalize its temperature before inflation occurred. As a result, you now live in a universe in which the background radiation has the same temperature in all directions.

The inflationary theory predicts that the universe is almost perfectly flat, which means that the actual density equals the critical density. A theory can never be used as evidence, of course, but the beauty and simplicity of the inflationary theory has given many cosmologists confidence that the universe must be flat. Observations, however, seem to say that the universe does not contain enough matter (ordinary baryonic matter plus nonbaryonic dark matter) to be flat. Can there be more to the universe than baryonic matter and dark matter? What could be weirder and more obscure than dark matter? Read on.

The Acceleration of the Universe

Both common sense and the theory of general relativity suggest that as the galaxies recede from each other, the expansion should be slowed by gravity trying to pull the galaxies toward each other. How much the expansion is slowed should depend on the amount of matter in the universe. If the density of matter and energy in the universe is less than the critical density, the

expansion should be slowing only somewhat, and the universe should expand forever. If the density of matter and energy is greater than the critical density, the expansion should be slowing down dramatically, and the universe should eventually begin contracting. Notice that this is the same as saying a low-density universe should be open and a high-enough-density universe should be closed.

For decades, astronomers struggled to measure the redshifts and distances to very distant galaxies and detect the slowing of the expansion. Detecting a change in the rate of expansion is difficult because it requires accurate measurements of the distances to very remote galaxies.

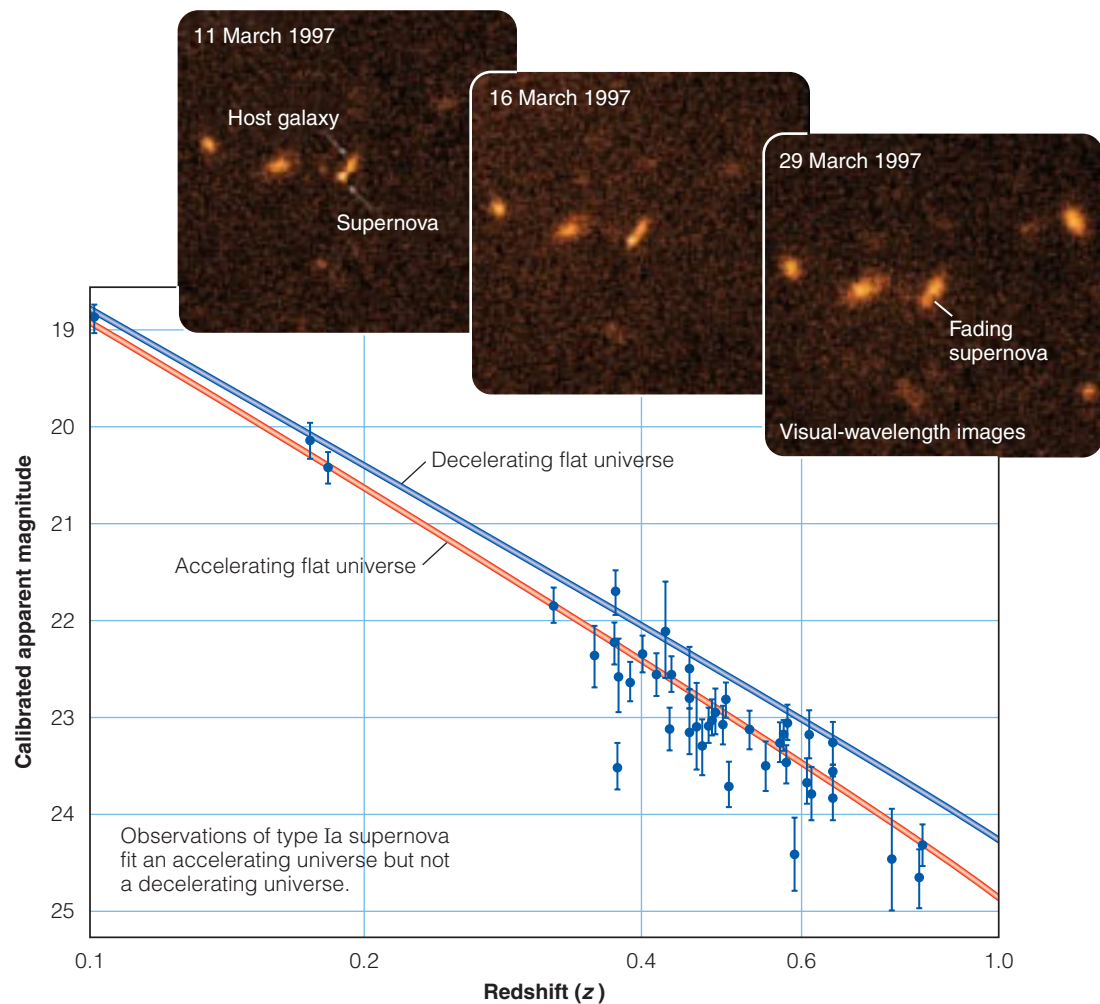
The launch of the Hubble Space Telescope in 1990 made it possible to measure distances to galaxies with unprecedented accuracy, and two competing research teams began using the same technique of calibrating type Ia supernovae as distance indicators. As you learned in Chapter 13, a type Ia supernova occurs when a white dwarf gains matter from a companion star, exceeds the Chandrasekhar limit, and collapses in a supernova explosion. Because all such white dwarfs should collapse at the same mass threshold, they should all produce explosions of the

same size and luminosity, which makes them good distance indicators.

The two teams calibrated type Ia supernovae by locating such supernovae occurring in nearby galaxies, with distances known from Cepheid variables and other reliable distance indicators. Once the peak luminosity of type Ia supernovae had been determined, they could be used to find the distances of much more distant galaxies.

Both teams announced their results in 1998. They agree that the expansion of the universe is not slowing down. Contrary to expectations, it is speeding up! That is, the expansion of the universe is accelerating (■ Figure 18-18).

The announcement that the expansion of the universe is accelerating was totally unexpected, and astronomers immediately began testing it. This result depends critically on the calibration of type Ia supernovae as distance indicators, and some astronomers suggested that the calibration might be wrong (look back to Figure 12-14 and “How Do We Know? 15-1”). Problems with the calibration have been ruled out subsequently by supernovae observed at even greater distances. The universe really does seem to be expanding faster and faster, rather than slowing down.



■ **Figure 18-18**

From the way supernovae fade over time, astronomers can identify those that are type Ia. Once calibrated, the peak brightness of each of those supernovae could be compared with their respective redshifts, revealing that distant type Ia supernovae were about 25 percent fainter than expected. That must mean they are farther away than expected, given their redshifts. This is strong evidence that the expansion of the universe is accelerating. (ESO)

Dark Energy and Acceleration

If the expansion of the universe is accelerating, then there must be a force of repulsion in the universe that counteracts gravity, and cosmologists are struggling to understand what it could be. One possibility leads back to 1916.

When Albert Einstein published his theory of general relativity in 1916, he recognized that his equations describing space-time implied that the galaxies could not float unmoving in space because their gravity would pull them toward each other. The only solutions seemed to be either a universe that was contracting under the influence of gravity or a universe in which the galaxies were rushing away from each other so rapidly that gravity could not pull them together. In 1916, cosmologists did not yet know that the universe was expanding, so Einstein made what he later thought was a mistake.

To balance the attractive force of gravity, Einstein added a constant to his equations called the **cosmological constant**, represented by an uppercase lambda (Λ). That constant represents a force of repulsion that balances the gravitational attraction between galaxies so the universe would not contract or expand. Thirteen years later, in 1929, Edwin Hubble announced his observations indicating that the universe is expanding, and Einstein said introducing the cosmological constant was his biggest blunder. Modern cosmologists think he may have been right after all.

One explanation for the acceleration of the universe is that there is, after all, a cosmological constant, representing a type of antigravity force that is part of the fabric of space-time and causes a continuing acceleration in the expansion of the universe. Because the cosmological constant by definition remains constant with time, the universe would have experienced this acceleration throughout its history.

Another solution is to suppose that totally empty space, the vacuum, contains energy that drives the acceleration. This is an interesting possibility because theoretical physicists have long discussed the idea of a vacuum energy for reasons based on the behavior of subatomic particles. Cosmologists label a universal vacuum energy as **quintessence**. Unlike the cosmological constant, the effect of quintessence would not necessarily remain constant over time.

Whatever the correct explanation might be, whether a cosmological constant antigravity force, or a universal vacuum energy, or something else, the observed acceleration of the universe's expansion is evidence that a type of unknown energy is spread throughout space. Cosmologists refer to it as **dark energy**, an energy that drives the acceleration of the universe but does not contribute to the formation of starlight or the cosmic microwave background radiation.

You will recall that acceleration and dark energy were first discovered when astronomers found that supernovae a few billion light-years away were slightly fainter than expected based on

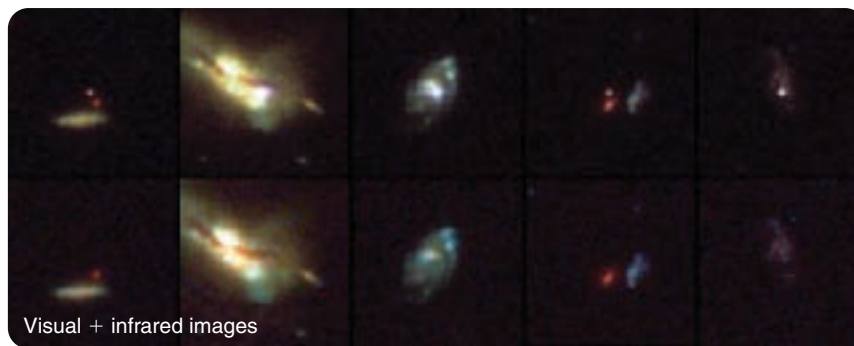
their redshifts. The acceleration of the expansion has made those supernovae a bit farther away than originally estimated from their redshifts, and so they look fainter. Since that discovery, astronomers have continued to find even more distant type Ia supernovae, some as distant as 12 billion light-years. The more distant of those supernovae are not too faint; they are too bright! That reveals even more about dark energy (■ Figure 18-19).

Unlike the medium-distant supernovae, the very distant supernovae are a bit too bright because they are not as far away as expected, and that confirms a theoretical prediction based on dark energy. When the universe was young, galaxies were closer together so their gravitational pull on each other was stronger than the effect of dark energy and slowed the expansion. That makes the very distant supernovae a bit too bright. As space-time expanded, it moved the galaxies farther apart, their gravitational pull on each other became weaker than dark energy, and acceleration began. That makes the medium-distant supernovae a bit too faint. In other words, the observations show that sometime about 6 billion years ago (when the universe was 55 percent of its present age), the universe shifted gears from deceleration to acceleration. The calibration of type Ia supernovae allows astronomers to observe this change from deceleration to acceleration.

Furthermore, dark energy can help you understand the curvature of the universe. The theory of inflation makes the specific prediction that the universe is flat. Recent observations you will learn about in the rest of this chapter confirm that prediction. Dark energy seems to explain how the universe can have enough matter plus energy to be flat. As you have already learned, $E=mc^2$ means that energy and matter are equivalent. Thus, the dark energy is equivalent to an amount of mass spread through space. Baryonic matter plus dark matter makes up about one-third of the critical density, and dark energy appears to make up the remaining two-

■ Figure 18-19

Follow-up observations of extremely distant galaxies located in the GOODS deep fields have detected type Ia supernovae. The upper images here show the supernovae, and the lower images show the galaxies before the supernovae erupted. These supernovae confirm the original discovery that the expansion of the universe is accelerating and are distant enough to eliminate concerns that the calibration of type Ia supernovae was wrong. (NASA, ESA, and Adam Riess, STScI)



thirds. That is, when you include dark energy, the total density of the universe equals the critical density, which makes the universe flat.

Step by step, you have been climbing the cosmological pyramid. Each step has been small and logical, but look where it has led you. You now know some of nature's deepest secrets, but you can imagine there are yet more steps above yet to be found, and more secrets to explore.

The Age and Fate of the Universe

Acceleration helps with another problem. The Hubble constant equals 70 km/s/Mpc, and earlier in this chapter you calculated the Hubble time, an estimate of the age of the universe, and found it was about 14 billion years. Further, you calculated a more precise estimate of the universe's age on the assumption that its geometry is flat, which gives an age of two-thirds of the Hubble time, or $\frac{2}{3}$ times 14 billion years, which equals about 9 billion years. That was a puzzle because the globular star clusters are older than that. Now you are really ready to solve the age problem and then consider the fate of the universe.

If the expansion of the universe has been accelerating, then it must have been expanding slower in the past, and the galaxies would have taken longer to arrive at the average separations you can observe now. That means the universe can be flat but nevertheless older than two-thirds of the Hubble time. The latest estimates suggest that acceleration makes the age of a flat universe almost 14 billion years, coincidentally about the same as the simple Hubble time estimate. That age is clearly older than the oldest known star clusters, which solves the age problem.

For many years, cosmologists have enjoyed saying, "Geometry is destiny." Thinking of open, closed, and flat universe models, they concluded that the density of a model universe determines its geometry, and its geometry determines its fate. By this they meant that if the universe is open it must therefore expand forever, whereas if it is closed, it must eventually begin contracting. But that is true only if the behavior of the universe as a whole is ruled completely by gravity. If dark energy causes an acceleration that can dominate gravity, then geometry is NOT destiny, and, depending on the precise properties of dark energy, even a closed universe might expand forever.

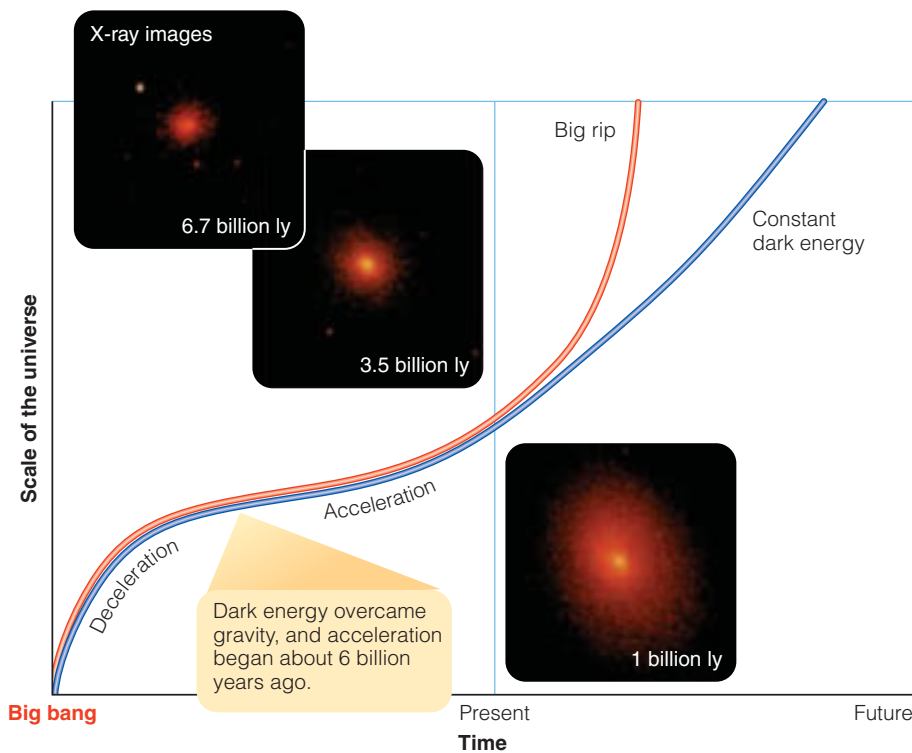
The ultimate fate of the universe depends on the nature of dark energy. If dark energy is described by the cosmological constant, then the force driving acceleration does not change with time, and our flat universe will expand forever with the galaxies getting farther and farther apart and using up their gas and dust making stars, and stars dying, until each galaxy is isolated, burnt out, dark, and alone. If, however, dark energy is

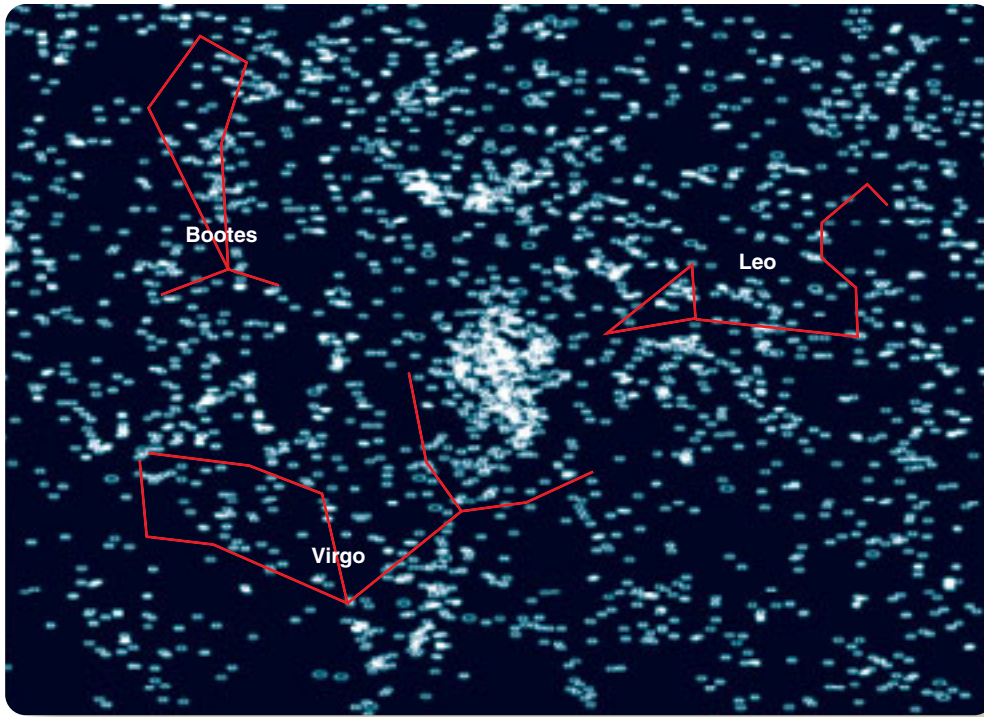
described by quintessence, then the force may be increasing with time, and the universe might accelerate faster and faster as space pulls the galaxies away from each other, eventually pulling the galaxies apart, then pulling the stars apart, and finally tearing individual atoms apart. This possibility has been called the **big rip**.

Probably there will be no big rip; critically important observations made by the Chandra X-ray Observatory have been used to measure the amount of hot gas and dark matter in almost 30 galaxy clusters. Because the distance of each cluster is one of the variables in the calculations, the X-ray astronomers could compare the amount of hot gas and dark matter and solve for distance. The farthest of the clusters is 8 billion light-years away. These observations are important for two reasons. First, the redshifts and distance of these galaxies independently confirm the conclusion from the supernova observations that the expansion of the universe first decelerated but changed to accelerating about 6 billion years ago. Second, the Chandra results almost completely rule out quintessence. If dark energy is described by the cosmological constant and not by quintessence, then there will be no big rip (■ Figure 18-20).

■ Figure 18-20

X-ray observations of hot gas in galaxy clusters confirm that in its early history the universe was decelerating because gravity was stronger than the dark energy. As expansion weakened the influence of gravity, dark energy began to cause acceleration. The evidence is not conclusive, but it most directly supports the cosmological constant form of dark energy and weighs against quintessence, which means the universe may not undergo a "big rip." This diagram is only schematic, and the two curves are drawn separated for clarity; at the present time, the two curves have not diverged from each other. (NASA/CXC/IoA/S. Allen et al.)





■ **Figure 18-21**

The distribution of brighter galaxies in the sky reveals the great Virgo cluster (center), containing over 1000 galaxies only about 17 Mpc away. Other clusters fill the sky, such as the more distant Coma cluster just above the Virgo cluster in this diagram. The Virgo cluster is linked with others to form the Local Supercluster.

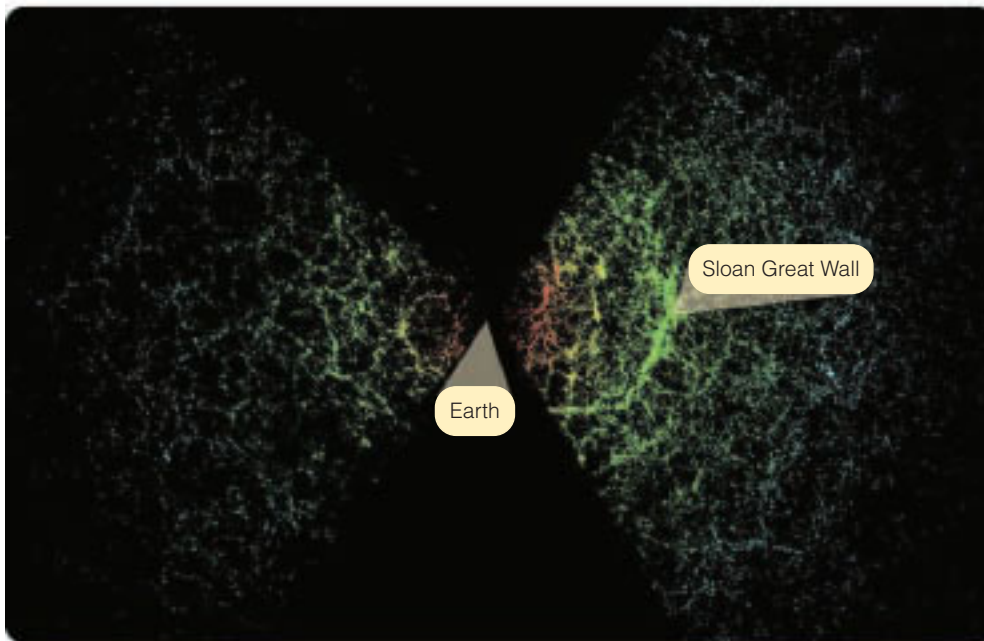
When you look at galaxies in the sky you see them in clusters ranging from a few galaxies to thousands, and those clusters appear to be grouped into **superclusters** (■ Figure 18-21). The Local Supercluster, in which you live, is a roughly disk-shaped swarm of galaxy clusters 50 to 75 Mpc in diameter. By measuring the redshifts and positions of hundreds of thousands

of galaxies in great slices across the sky, astronomers have been able to create maps revealing that superclusters are not scattered at random. They are distributed in long, narrow **filaments** and thin walls that outline great **voids** nearly empty of galaxies (■ Figure 18-22).

This large-scale structure is a problem because the cosmic microwave background radiation is very uniform, and that means the gas of the big bang must have been extremely uniform at the time of recombination. Yet the look-back time to the

The Origin of Large-Scale Structure

On the largest scales, the universe is isotropic. That is, it looks the same in all directions. But, on smaller scales, there are irregularities. The sky is filled with galaxies and clusters of galaxies that seem to be related to their neighbors in even larger aggregations that astronomers call **large-scale structure**. Studies of large-scale structure lead to insights about how the universe has evolved.



■ **Figure 18-22**

Nearly 70,000 galaxies are plotted in this double slice of the universe extending outward in the plane of Earth's equator. The nearest galaxies are shown in red and the more distant in green and blue. The galaxies form filaments and walls enclosing nearly empty voids. The Sloan Great Wall is almost 1.4 billion light-years long and is the largest known structure in the universe. The most distant galaxies in this diagram are roughly 3 billion light-years from Earth. (Sloan Digital Sky Survey)

farthest galaxies and quasars is about 93 percent of the way back to the big bang. How did the uniform gas at the time of recombination become lumpy and coagulate so quickly to form galaxies? How did it make clusters of galaxies and the supermassive black holes we observe as quasars (see Chapter 17) so early in the history of the universe?

Baryonic matter is so rare in the universe that cosmologists can calculate that it did not have enough gravity to pull itself together quickly after the big bang. As you learned earlier, cosmologists have evidence that dark matter is nonbaryonic and therefore immune to the intense radiation that prevented normal matter from contracting. Dark matter, in contrast, was able to collapse into clouds and then attract normal matter to begin the formation of galaxies, clusters, and superclusters. Mathematical models have been made to describe this process, and cold dark matter does seem capable of jump-starting the formation of structure of the right sizes and in the right amount of time (■ Figure 18-23).

But what started the clumping of the dark matter? Theorists say that space is filled with tiny, random quantum mechanical fluctuations smaller than the smallest atomic particles. At the moment of inflation, those tiny fluctuations would have been stretched to very large but very subtle variations in gravitational fields that could have stimulated the formation of galaxy superclusters, filaments, and walls. The structure you see in Figure 18-22 may be the present-day ghostly traces of microscopic random fluctuations in the infant universe.

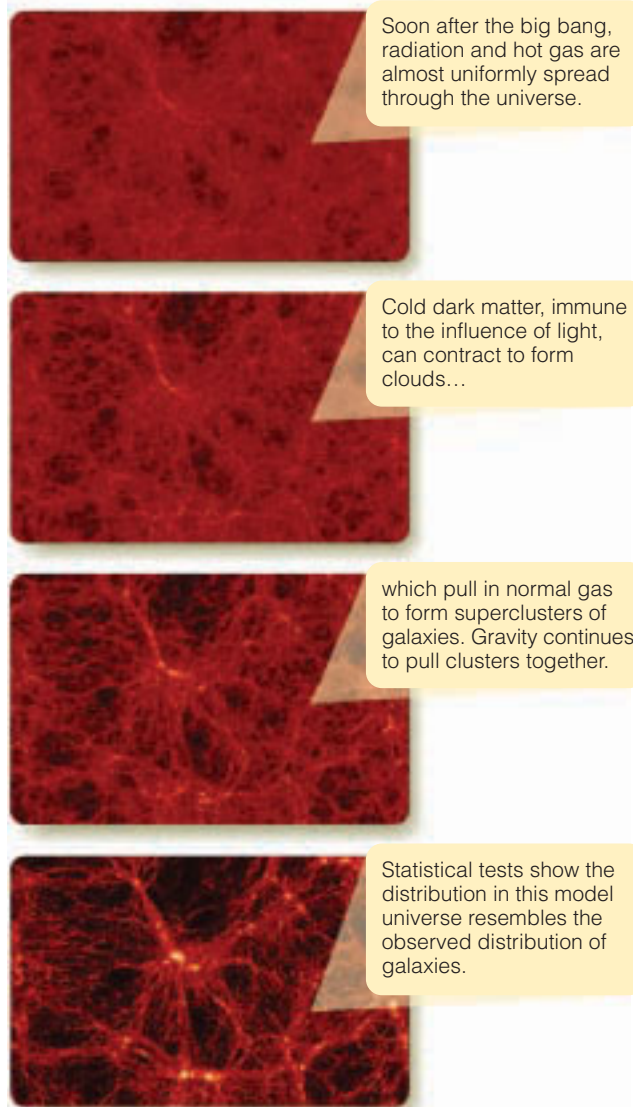
The Two-Degree-Field Redshift Survey mapped the position and redshift of 250,000 galaxies and 30,000 quasars. As expected, the galaxies are spread in filaments and walls, and a statistical analysis of the distribution matches the prediction of inflation and shows that the universe expansion is accelerating. This is an important result because it is yet another confirmation of acceleration that is independent of the brightness of type Ia supernovae or X-ray-emitting gas in galaxy clusters. When a hypothesis is confirmed by observations of many different types, scientists have much more confidence that it is a true description of nature.

Curvature of the Universe

Astronomers continue to search for more ways to confirm that the universe is flat and that its expansion is accelerating. One way to measure the curvature of space-time is to measure the size of things at great look-back times; for example, observing irregularities in the background radiation. That type of measurement is yielding impressive results.

The background radiation is nearly isotropic—it looks almost exactly the same in all directions after effects of Earth’s motion and emission by material in the foreground are taken into account. After those corrections are made to a map of the background radiation and the average intensity is subtracted from each spot on the sky, minor irregularities are evident. That is, some spots on the sky look a tiny bit hotter and brighter, or cooler and fainter, than

Growth of Structure in the Universe

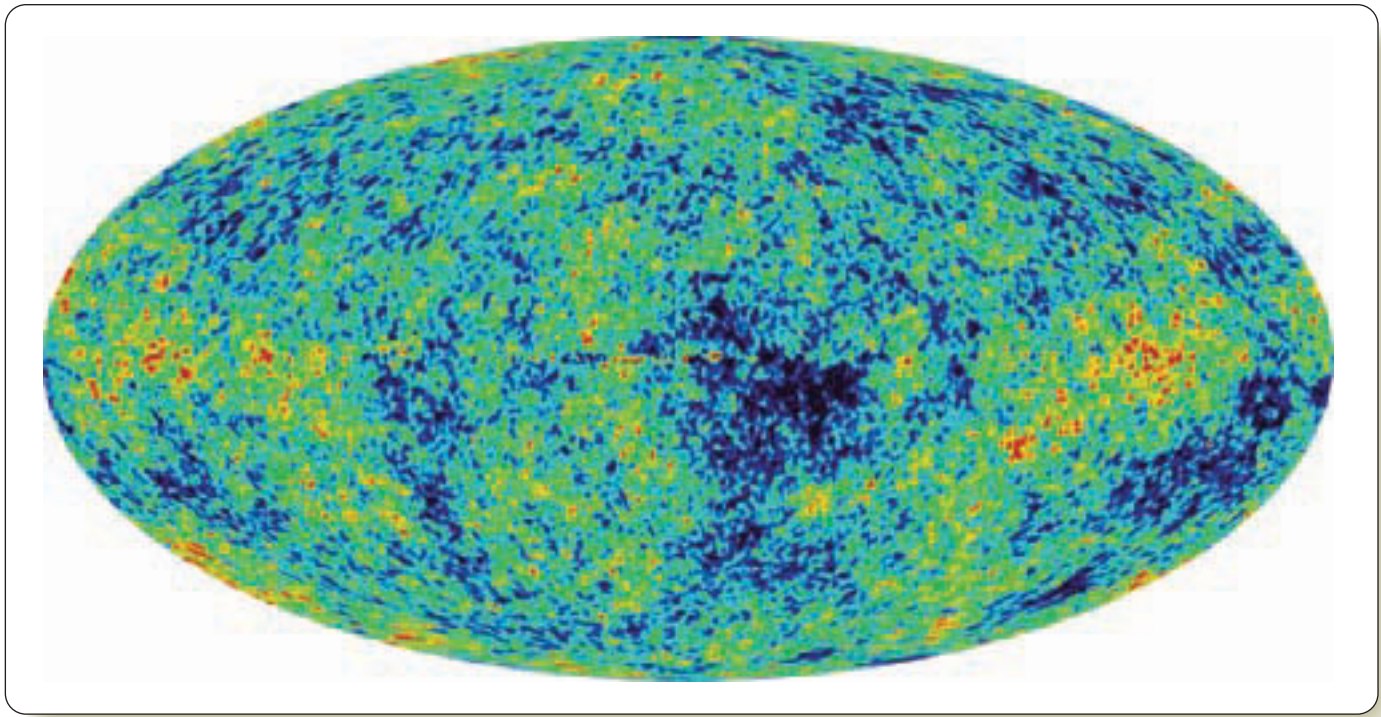


■ **Figure 18-23**

This computer model traces the formation of structure in the universe from soon after the big bang to the present. (Adapted from a model by Kauffmann, Colberg, Diaferio, & White: Max-Planck Institut für Astronomie)

the average (■ Figure 18-24; also look back at Figure 18-8). Those irregularities contain lots of information.

The inflation-modified big bang theory of the universe makes specific predictions about the angular sizes of the variations you should find in the background radiation. Observations made by the COBE satellite in 1992 detected the variations with the largest diameter, but detecting smaller variations is critical for testing the theory. Six teams of astronomers have built specialized telescopes to make these observations. Some have flown under balloons high in the atmosphere, and others have observed from the ice of Antarctica. Extensive observations of the background



■ **Figure 18-24**

Data from the WMAP spacecraft were used to make this far-infrared map of the entire sky. The infrared glow from dust in our solar system and in the Milky Way Galaxy has been removed to reveal slight irregularities in the temperature of the cosmic microwave background radiation. Red and yellow spots are slightly warmer than the green and blue spots. (NASA/WMAP Science Team)

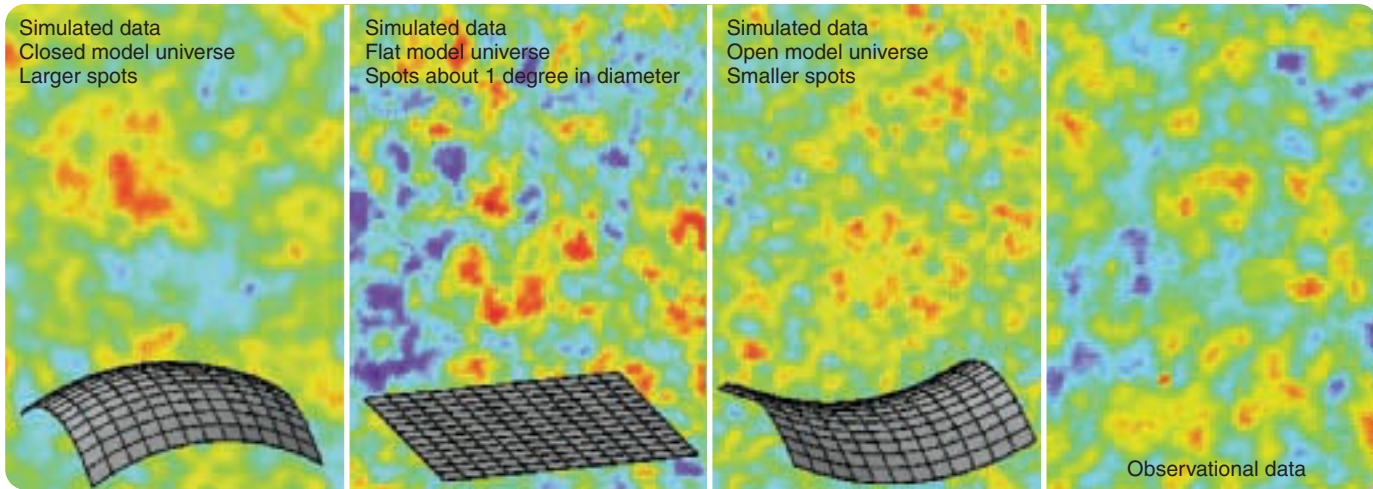
radiation have been made by the Wilkinson Microwave Anisotropy Probe (WMAP). In 2009 the Planck space telescope was launched to do an even more thorough job.

It is a **Common Misconception** that explosions in space produce sound. Science-fiction movies imply that sound can travel through a vacuum and that exploding space ships make big *kabooms*. That's not true now, of course, but the early universe was dense enough that sound could travel through the gas, and the big bang did make a noise. A theorist described it as “a descending scream, building to a deep rasping roar, and ending in a deafening hiss.” The pitch of the sound was about 50 octaves too low for you to hear, but those powerful sound waves did have an effect on the universe. They determined the size of the irregularities now detectable in the cosmic microwave background radiation.

Theory predicts that most of the irregularities in the hot gas of the big bang should be about one degree in diameter if the universe is flat. If the universe were open, the most common irregularities would be smaller. Careful measurements of the size of the irregularities in the cosmic background radiation show that the observations fit the theory very well for a flat universe, as you can see in ■ Figure 18-25. Not only is the theory of inflation confirmed, an exciting result itself, but these data show that the universe is flat, meaning space-time has no overall curvature, which indirectly confirms the existence of dark energy and the acceleration of the universe.

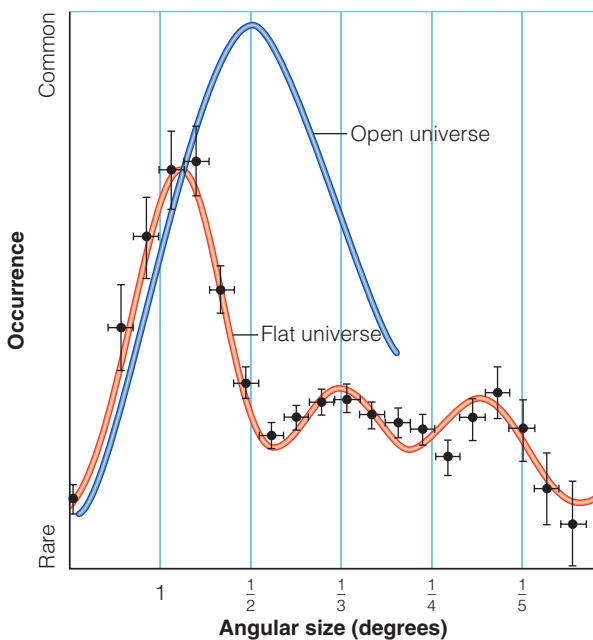
Cosmologists can analyze those microwave background irregularities using sophisticated mathematics to find out how frequently spots of different angular sizes occur. The calculations confirm that spots about 1 degree in diameter are the most common, but spots of other sizes occur as well, and it is possible to plot a graph such as ■ Figure 18-26 to show how frequently different sizes of irregularities occur.

The data points from the WMAP observations follow a wiggling line in Figure 18-26, and the size and positions of those wiggles tell cosmologists a great deal about the universe. The details of the curve show that the universe is flat, accelerating, and will expand forever. The age of the universe derived from the data is 13.7 billion years. Furthermore, the smaller peaks in the curve reveal that the universe contains 4.6 percent baryonic (normal) matter, 23.3 percent nonbaryonic dark matter, and 72.1 percent dark energy. The Hubble constant is confirmed to be 71 km/s/Mpc. The inflationary theory is confirmed, and the data give more support to the cosmological constant version of dark energy, although quintessence is not quite ruled out. Hot dark matter is ruled out. The dark matter needs to be cold dark matter to clump together rapidly enough after the big bang to make the galaxy clusters and superclusters we observe. In fact, a model based on these data predicts that the first stars began to produce light when the universe was only about 400 million years old.



■ **Figure 18-25**

You can see the difference yourself. Compare the observations of the irregularities in the background radiation in the far right panel with the three simulations starting from the left. The observed size of the irregularities fits best with cosmological models having flat geometry. Detailed mathematical analysis confirms your visual impression: The universe is flat. (Courtesy of the BOOMERANG Collaboration)



■ **Figure 18-26**

This graph shows how commonly irregularities of different sizes occur in the cosmic microwave background radiation. Irregularities of about 1 degree in diameter are most common. Models of the universe that are open or closed are ruled out. The data fit a flat model of the universe very well. Crosses on data points show the uncertainty in the measurements.

Please reread the preceding paragraph. Especially to people who have been working in the field for years, that collection of firm facts is mind-blastingly amazing. WMAP and other studies

of the cosmic microwave background radiation and the distribution of galaxies have revolutionized cosmology. At last, astronomers have accurate observations against which to test theories. The values of the basic cosmic parameters are known to a precision of 1 percent or better.

On reviewing these results, one cosmologist announced that “Cosmology is solved!” but that might be premature. Cosmologists don’t understand dark matter or the dark energy that drives the acceleration, so in a sense, over 95 percent of the universe is not understood. Hearing this, another cosmologist suggested a better phrase was “Cosmology in crisis!” Certainly there are further mysteries to be explored, but cosmologists are growing more confident that they can describe the origin and evolution of the universe.

SCIENTIFIC ARGUMENT

How does inflation theory solve the flatness problem?

This question requires a carefully constructed argument. The flatness problem can be stated as a question: Why is the universe so flat? After all, the density of matter in the universe could be anything from zero to infinite, but the observed sizes of variations in the cosmic background radiation show that the universe is flat, and therefore the average density of the universe is very close to the critical density (Figures 18-25 and 18-26). Furthermore, the density must have been astonishingly close to the critical density when the universe was very young, or it would not be as close as it is now. The inflationary theory solves this problem by proposing that the universe had a moment of rapid inflation when it was a tiny fraction of a second old. That inflation drove the universe toward flatness just as blowing up a balloon makes a spot on the balloon flatter and flatter.

Understanding theory in cosmology is critically important, but science depends on evidence. Now build another argument based on evidence. **What evidence can you cite that the expansion of the universe is accelerating?**

What Are We? The Big Picture

As you climbed the cosmology pyramid, you negotiated many steps. Most were easy, and all were logical. They have carried you up to some sweeping views, and you have traced the origin of the universe, the formation of the chemical elements, the birth of galaxies, and the births and deaths of stars. You now have a perspective that few humans share.

We are by-products of two cosmic processes, gravitational contraction and nuclear fusion. Gravity created instabilities

in the hot matter of the big bang and triggered the formation of clusters of galaxies. Further contraction of that material formed individual galaxies and then stars within the galaxies. As stars began to shine through the universe, nuclear fusion in their cores began to cook hydrogen and helium into the heavier atoms from which humans are made.

As you review the history and structure of the universe, it is wise to recognize the

mysteries that remain; but note that they are mysteries that may be solved rather than mysteries that are unknowable. Only a century ago, humanity didn't know there were other galaxies, or that the universe was expanding, or that stars generate energy by nuclear fusion. Human curiosity has solved many of the mysteries of cosmology and will solve more during your lifetime.

Study and Review

Summary

- ▶ **Cosmology (p. 370)** is the study of the structure and history of the universe as a whole. Astronomers and physicists who do research in cosmology are called **cosmologists (p. 371)**.
- ▶ Cosmologists conclude that it is impossible for the universe to have an edge because an edge would introduce logical inconsistencies. In other words, an edge to the universe does not make sense.
- ▶ If the universe has no edge, then it cannot have a center.
- ▶ The darkness of the night sky leads to the conclusion that the universe is not infinitely old. If the universe were infinite in extent, infinite in age, and **static (p. 371)**, then every spot on the sky would glow as brightly as the surface of a star. This problem, commonly labeled **Olbers's paradox (p. 371)**, implies that the universe had a beginning and is evolving.
- ▶ The **observable universe (p. 372)**, the part you can see from Earth with a large telescope, is limited in size. It may be only a tiny portion of the entire universe, which could be infinite.
- ▶ Edwin Hubble's 1929 discovery that the redshift of a galaxy is proportional to its distance, now known as the Hubble law, shows that the galaxies appear to be moving away from each other. That phenomenon is called the **expanding universe (p. 372)**.
- ▶ Tracing the expansion of the universe backward in time brings you to imagine an initial high-density, high-temperature state commonly called the **big bang (p. 373)**.
- ▶ A rough estimate of the age of the universe based on the presently observed expansion rate is called the **Hubble time (p. 374)**.
- ▶ Although the expanding universe began from the big bang, it has no center. The galaxies do not move away from a single point. Cosmologists understand that galaxies remain approximately in their respective positions and are carried away from each other as the space between them expands.
- ▶ The **cosmic microwave background (p. 375)** radiation is blackbody radiation with a temperature of about 2.73 K, spread nearly uniformly over the entire sky. This radiation is the light from the big bang, freed from the gas at the time of **recombination (p. 378)** and now redshifted by a factor of 1100.
- ▶ The background radiation is clear evidence that the universe began with a big bang.
- ▶ During the earliest moments of the universe, matter and **antimatter (p. 376)** particles continually flashed in and out of existence. A slight excess of ordinary matter remained after most of the matter and antimatter particles annihilated each other.
- ▶ During the first few minutes of the big bang, nuclear fusion converted some of the hydrogen into helium but was unable to make many other heavy atoms because no stable nuclei exist with weights of 5 or 8. Now, hydrogen and helium are common in the universe, but heavier atoms are rare.
- ▶ After recombination, for a period of hundreds of millions of years called the **dark age (p. 378)**, the universe expanded in darkness until the first stars came into existence. Astronomers have observed signs of **reionization (p. 378)** of the universe caused by that first generation of stars.
- ▶ The chemical composition of the oldest stars is about 75 percent hydrogen and 25 percent helium, which is what models of the big bang nuclear processes would predict. This is further evidence supporting the big bang theory.
- ▶ The universe is **isotropic (p. 380)** and **homogeneous (p. 380)**. In other words, in its major features, the universe respectively looks the same in all directions from Earth and appears to have the same properties in all locations.
- ▶ Isotropy and homogeneity lead to the **cosmological principle (p. 380)**, the idea that there are no special places in the universe. Except for minor local differences, every place is the same, and the view from every place is the same.

- ▶ Einstein's theory of general relativity explains that cosmic redshifts are caused by wavelengths of photons stretching as they travel through expanding space-time.
- ▶ **Closed universe (p. 381)** models are finite in size, but their space-time is curved back on itself so they have no edge or center.
- ▶ **Flat universe (p. 381)** models have uncurved space-time and are infinite. Modern observations show that the universe is probably flat.
- ▶ **Open universe (p. 381)** models have curved space-time, but it is not curved back on itself. Such universes are infinite. Open model universes contain less than the **critical density (p. 382)** and closed model universes more. If the universe is flat, then its density must equal the critical density.
- ▶ The amounts of deuterium and lithium-7 in the universe shows that normal baryonic matter can make up only about 5 percent of the critical density. Dark matter must be **nonbaryonic (p. 383)** and makes up less than 30 percent of the critical density.
- ▶ One suggestion for what dark matter might be is a hypothetical type of subatomic particle labeled **WIMPs (p. 383)**. The observed ranges of sizes and masses for galaxy clusters disagrees with models that assume rapidly moving **hot dark matter (p. 383)** particles that would not clump together easily and, instead, agrees with models that assume slowly moving, readily-clumping **cold dark matter (p. 383)**.
- ▶ The **inflationary universe (p. 385)**, a modification to the big bang theory, proposes that the universe briefly expanded dramatically, just a tiny fraction of a second after the big bang.
- ▶ The energy to drive inflation would have been released when the four forces of nature changed their respective properties to become different as the universe cooled in its earliest moments. This "separation" of forces is predicted by **grand unified theories (GUTs) (p. 385)** that explain the forces of nature as being aspects of a single force and that are unified only in particle interactions with very high energies.
- ▶ Inflation explains the **flatness problem (p. 384)** because the large expansion forced the universe to become flat, just as a spot on an inflating balloon becomes flatter as the balloon inflates.
- ▶ Inflation explains the **horizon problem (p. 384)** because what is now the observable part of the universe was so small before inflation that energy could move and equalize the temperature everywhere in that volume.
- ▶ Observations of type Ia supernovae reveal the surprising fact that the expansion of the universe is speeding up. Cosmologists propose that this acceleration is caused by energy present in empty space labeled "**dark energy**" (p. 387).
- ▶ The nature of dark energy is unknown. It may be described by Einstein's **cosmological constant (Λ) (p. 387)**, or its strength may change with time, which cosmologists label "**quintessence**" (p. 387). Some models of quintessence predict an ever-accelerating expansion leading to a "**big rip**" (p. 388) that eventually would tear all the objects, even the atoms, of the universe apart.
- ▶ Corrected for acceleration, the observed value of the Hubble constant implies that the universe is 13.7 billion years old.
- ▶ The sudden inflation of the universe is hypothesized to have magnified tiny quantum mechanical fluctuations in the density of matter and energy. These very wide but very weak differences in density caused dark matter, followed by baryonic matter, to draw together and produce the present-day **large-scale structure (p. 389)** consisting of galaxy **superclusters (p. 389)** arranged in great walls and **filaments (p. 389)** outlining enormous **voids (p. 389)**.
- ▶ Statistical observations of the large-scale structure of the universe and the size of irregularities in the cosmic microwave background confirm that it is flat and contains 4.6 percent baryonic matter, 23.3 percent dark matter, and 73.1 percent dark energy.

- ▶ The mass equivalent of dark energy added to dark matter and baryonic matter makes the observed density of the universe equal to the critical density, thereby confirming the prediction made by inflation theory that the universe is flat.

Review Questions

1. How does the darkness of the night sky tell you something important about the universe?
2. How can Earth be located at the center of the observable universe if you accept the cosmological principle?
3. Why can't an open universe have a center? How can a closed universe not have a center?
4. What evidence shows that the universe is expanding? What evidence shows that it began with a big bang?
5. Why couldn't atomic nuclei exist when the age of the universe was less than 2 minutes?
6. Why are measurements of the present density of the universe important?
7. How does the inflationary universe theory resolve the flatness problem? How does it resolve the horizon problem?
8. If the Hubble constant were really 100 instead of 70 km/s/Mpc, much of what astronomers understand about the evolution of stars and star clusters would have to be wrong. Explain why. (*Hint: What would the age of the universe be?*)
9. What is the evidence that the universe was very uniform during its first 400,000 years?
10. What is the difference between hot dark matter and cold dark matter? What difference does that make to cosmology?
11. What evidence can you cite that the expansion of the universe is accelerating?
12. What evidence can you cite that the universe is flat?
13. **How Do We Know?** Reasoning by analogy often helps make complicated systems or abstract ideas easier to understand. Why do you have to be careful when using analogies?
14. **How Do We Know?** The word *believe* has a meaning in normal conversation that does not really apply to scientific work. Why might cosmologists hesitate to use the word "believe" when they talk about the big bang?

Discussion Questions

1. Do you think Copernicus would have accepted the cosmological principle? Why or why not?
2. If you reject any model of the universe that has an edge in space because you can't comprehend such a thing, shouldn't you also reject any model of the universe that has a beginning? Isn't a beginning like an "edge" in time, or is there a difference?

Problems

1. Use the data in Figure 18-4 to plot a velocity–distance diagram, calculate the Hubble constant H , and estimate the Hubble time.
2. If a galaxy is 9.0 Mpc away from Earth and recedes at 510 km/s, what is H ? What is the Hubble time? How old would the universe be, assuming space-time is flat and there has been no acceleration of the universe's expansion? How would acceleration change your answer?
3. What was the wavelength of maximum intensity for radiation from the gas of the big bang at the time of recombination? By what factor

is that different from the wavelength of maximum intensity of the cosmic microwave background radiation observed now?

4. Pretend that galaxies are spaced evenly, 2 Mpc apart, and the average mass of a galaxy is 10^{11} solar masses. What is the average density of matter in the universe? (*Hints:* The volume of a sphere is $\frac{4}{3}\pi r^3$, and the mass of the sun is 2×10^{30} kg.)
5. Figure 18-14 is based on an assumed Hubble constant of 70 km/s/Mpc. How would you change the diagram to fit a Hubble constant of 50 km/s/Mpc?
6. Hubble's first estimate of the Hubble constant was 530 km/s/Mpc. His distances were too small by a factor of about 7 because of a calibration error. If he had not had that calibration problem, what value for H would he have obtained?
7. What was the maximum age of the universe predicted by Hubble's first estimate of the Hubble constant (in Problem 6)?

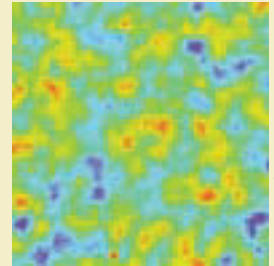
Learning to Look

1. Explain why some of the galaxies in this photo have elongated, slightly curved images. What do such observations tell you about the universe?



NASA/ACS Science Team/ESA

2. The image at the right shows irregularities in the background radiation. Why isn't the background radiation perfectly uniform? What does the size of these irregularities tell you?

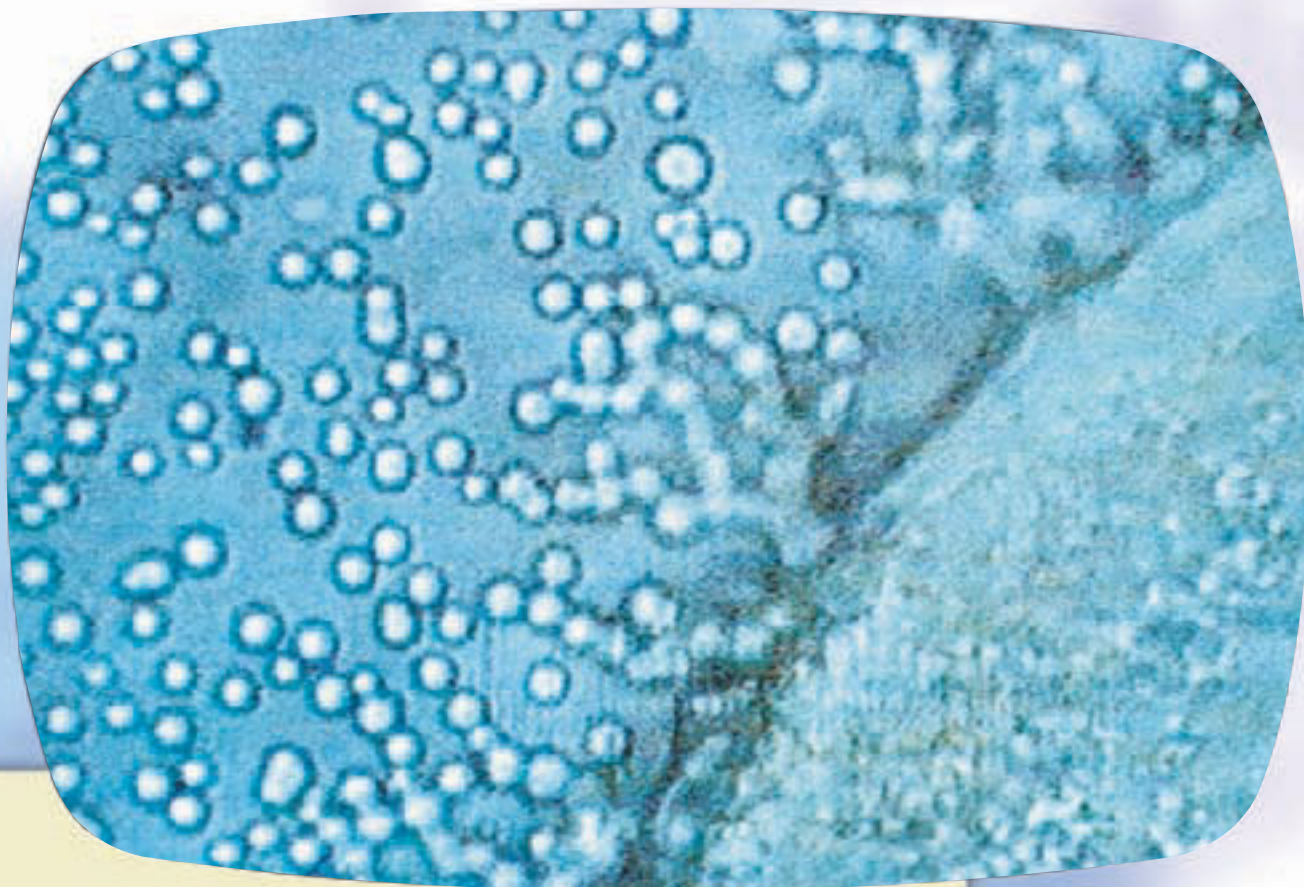


Courtesy of BOOMERANG Collaboration

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19

Astrobiology: Life on Other Worlds



Guidepost

This chapter is either unnecessary or vital. You have studied the sun, stars, galaxies, and the origin of the universe. If you believe that's all you need from an astronomy course, you are done; the previous 18 chapters have completed your journey. But, if you believe that astronomy should include not only the study of the distant universe but also your role and the role of the Earth's other living beings in the evolution of the universe, then everything you have learned so far from this book has been preparation for this final chapter.

As you read this chapter, you will ask four important, related questions:

— **What is life?**

— **How did life originate on Earth?**

— **Could life begin on other worlds?**

— **Can humans on Earth communicate with civilizations on other worlds?**

You won't get more than the beginnings of answers to those questions here, but often in science asking a question is more important than getting an immediate answer.

You have explored the universe from the phases of the moon to the big bang, from the origin of Earth to the death of the sun. Astronomy is meaningful, not just because it is about the universe but because it is also about you. Now that you know astronomy, you see yourself and your world in a different way. Astronomy has changed you.

Single amino acids can be assembled into long proteinlike molecules. When such material cools in water, it often forms microspheres, tiny globules with double-layered boundaries similar to cell membranes. Microspheres may have been an intermediate stage in the evolution of life between complex but nonliving molecules and living cells holding genetic information.
(Sidney Fox and Randall Grubbs)

Did I solicit thee from darkness to promote me?

— ADAM, TO GOD, IN JOHN MILTON'S *PARADISE LOST*

AS A LIVING THING, you have been promoted from darkness. The atoms of carbon, oxygen, and other heavy elements that are necessary components of your body did not exist at the beginning of the universe but were built up by successive generations of stars.

The elements from which you are made are common everywhere in the observable universe, so it is possible that life began on other worlds and evolved to intelligence. If so, perhaps those other civilizations will be detected from Earth. Future astronomers may discover distant alien species completely different from any life on Earth.

Your goal in this chapter is to try to understand truly intriguing puzzles—the origin and evolution of life on Earth and what that tells you about whether there is life on other worlds (**How Do We Know? 19-1**). This new hybrid field of study is called **astrobiology**.

19-1 The Nature of Life

WHAT IS LIFE? Philosophers have struggled with that question for thousands of years, and it is not possible to answer it completely in one chapter or even one book. An attempt at a general

definition of what living things do, distinguishing them from nonliving things, might be: Life is a *process* by which an organism extracts energy from the surroundings, maintains itself, and modifies the surroundings to foster its own survival and reproduction.

One very important observation is that all living things on Earth, no matter how apparently different, share certain characteristics in how they perform the process of life.

The Physical Basis of Life

The physical basis of life on Earth is the element carbon (■ Figure 19-1). Because of the way carbon atoms bond to each other and to other atoms, they can join into long, complex, stable chains that are capable, among many other feats, of storing and transmitting information. A large amount of information is necessary to control the activities and maintain the forms of living things.

It is possible that life on other worlds could use silicon instead of carbon. Silicon is right below carbon in the periodic table (Appendix Table A-16), which means that it shares many of carbon's chemical properties. But life based on silicon rather than carbon seems unlikely because silicon chains are harder to assemble and disassemble than their carbon counterparts and can't be as lengthy. Science fiction has proposed even stranger life forms based on, for example, electromagnetic fields and ionized gas, and none of these possibilities can be ruled out. Those hypothetical life forms make for fascinating speculation, but for now they can't be studied systematically in the way that life on Earth can.

■ **Figure 19-1**

All living things on Earth are based on carbon chemistry. Even the long molecules that carry genetic information, DNA and RNA, have a framework defined by chains of carbon atoms. (a) Ana, a complex mammal, contains about 60 AU of DNA. (Jamie Backman) (b) Each rod-like tobacco mosaic virus contains a single spiral strand of RNA about 0.01 mm long as its genetic material. (L. D. Simon)



The Nature of Scientific Explanation

Must science and religion be in conflict?

Science is a way of understanding the world around you, and at the heart of that understanding are explanations that science gives for natural phenomena. Whether you call these explanations stories, histories, hypotheses, or theories, they are attempts to describe how nature works based on evidence and intellectual honesty. While you may take these explanations as factual truth, you can understand that they are not the only explanations that describe the universe.

A separate class of explanations involves religion. For example, the Old Testament description of creation does not fit well with scientific observations, but it is a way of understanding the universe nonetheless. Religious explanations are based partly on faith rather than on strict rules of logic and evidence, and it is wrong to demand that they follow the same rules as scientific explanations. In the same way, it is wrong to demand that scientific explanations take into account religious beliefs. The so-called conflict between science and religion arises

when people fail to recognize that science and religion are different ways of knowing about the universe.

Scientific explanations are very compelling because science has been very successful at producing technological innovations that have changed the world you live in. From new vaccines, to digital music players, to telescopes that can observe the most distant galaxies, the products of the scientific process are all around you. Scientific explanations have provided tremendous insights into the workings of nature. Many people are attracted to the suggestion, made by evolutionary biologist Stephen Jay Gould and others, that religious explanations and scientific explanations should be considered as “separate magisteria.” In other words, religion and science are devoted to different realms of the mystery of existence.

Science and religion offer differing ways of explaining the universe, but the two ways follow separate rules and cannot be judged by each other’s standards. The trial of Galileo can be understood as a conflict between these two ways of knowing.



Galileo's telescope gave him a new way to know about the universe.

This chapter is concerned with the origin and evolution of life as it is on Earth, based on carbon, not because of lack of imagination but because it is the only form of life about which we know anything.

Even carbon-based life has its mysteries. What makes a lump of carbon-based molecules a living thing? An important part of the answer lies in the transmission of information from one molecule to another.

Information Storage and Duplication

Most actions performed by living cells are carried out by molecules that are built within the cells. Cells must store recipes for making all those molecules, as well as how and when to use them, and then somehow pass the recipes on to their offspring.

Study **DNA: The Code of Life** on pages 400–401 and notice four important points and seven new terms:

1 The chemical recipes of life are stored in each cell as information on *DNA* (*deoxyribonucleic acid*) molecules that resemble a ladder with rungs that are composed of chemical bases. The recipe information is expressed by the sequence of

the rungs, providing instructions to guide specific chemical reactions within the cell.

2 The instructions stored in DNA are genetic information passed along to offspring. DNA instructions normally are expressed by being copied into a messenger molecule called *RNA* (*ribonucleic acid*). The RNA molecule travels to a location in the cell where its message causes a sequence of molecular units called *amino acids* to be connected into large molecules called *proteins*. Proteins serve as the cell’s basic structural molecule or as *enzymes* that control chemical reactions.

3 The DNA molecule reproduces itself when a cell divides so that each new cell contains a copy of the original information. A sequence of DNA that composes one instruction is called a *gene*. Genes are organized into long coiled chains called *chromosomes*. The genes linked on one chromosome are normally passed on to offspring together.

To produce viable offspring, a cell must be able to make copies of its DNA. Surprisingly, it is important for the continued existence of all life that the copying process includes mistakes.

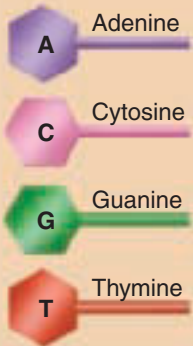
DNA: The Code of Life

1 The key to understanding life is information — the information that guides all of the processes in an organism. In most living things on Earth, that information is stored on a long spiral molecule called **DNA** (deoxyribonucleic acid).

1a The DNA molecule looks like a spiral ladder with rails made of phosphates and sugars. The rungs of the ladder are made of four chemical bases arranged in pairs. The bases always pair the same way. That is, base A always pairs with base T, and base G always pairs with base C.

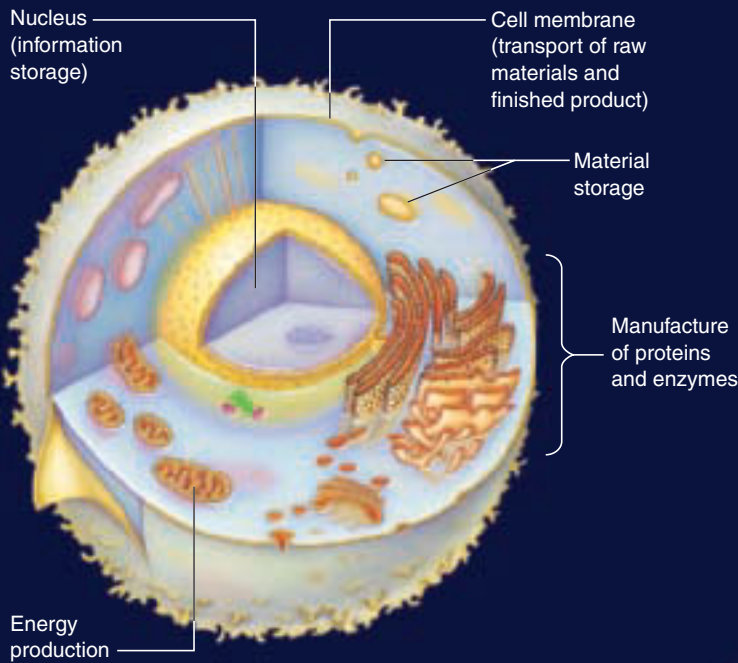
1b Information is coded on the DNA molecule by the order in which the base pairs occur. To read that code, molecular biologists have to “sequence the DNA.” That is, they must determine the order in which the base pairs occur along the DNA ladder.

The Four Bases



The traits you inherit from your parents, the chemical processes that animate you, and the structure of your body are all encoded in your DNA. When people say “you have your mother’s eyes,” they are talking about DNA codes.

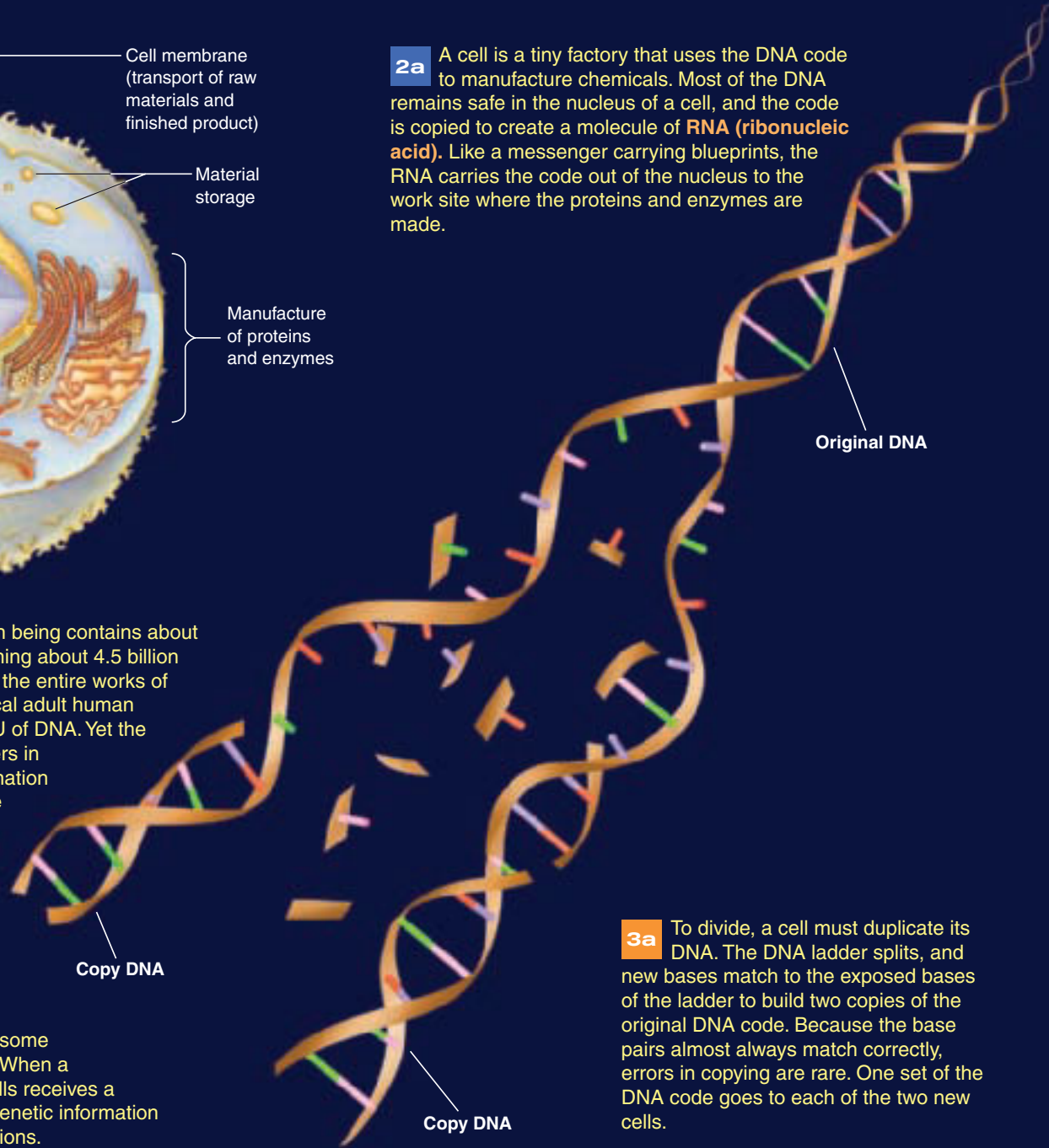
2 DNA automatically combines raw materials to form important chemical compounds. The building blocks of these compounds are relatively simple **amino acids**. Segments of DNA act as templates that guide the amino acids to join together in the correct order to build specific **proteins**, chemical compounds important to the structure and function of organisms. Some proteins called **enzymes** regulate metabolic processes. In this way, DNA recipes regulate the production of the compounds of life.



2a A cell is a tiny factory that uses the DNA code to manufacture chemicals. Most of the DNA remains safe in the nucleus of a cell, and the code is copied to create a molecule of **RNA (ribonucleic acid)**. Like a messenger carrying blueprints, the RNA carries the code out of the nucleus to the work site where the proteins and enzymes are made.

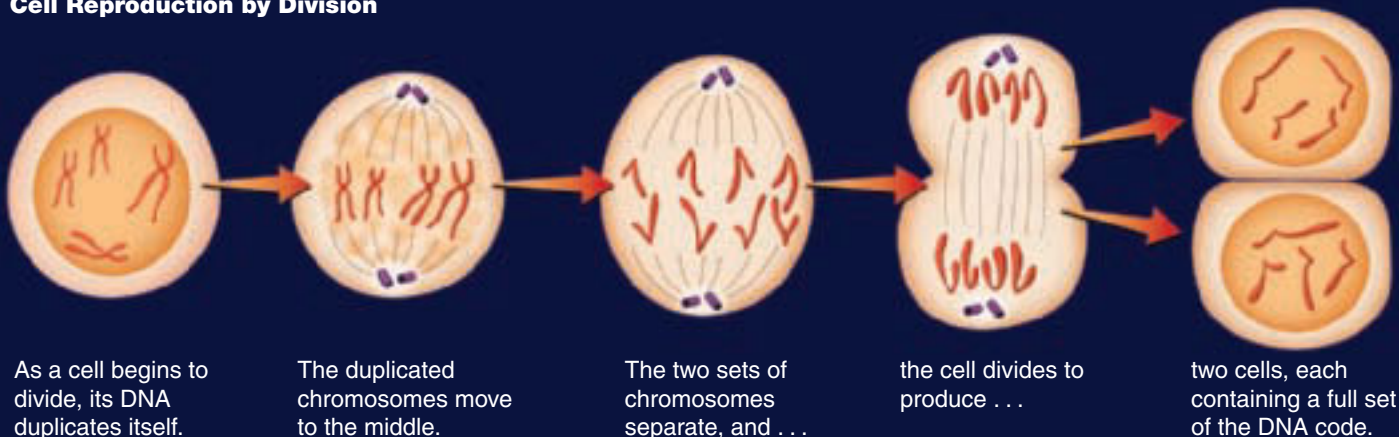
2b A single cell from a human being contains about 1.5 meters of DNA containing about 4.5 billion base pairs — enough to record the entire works of Shakespeare 200 times. A typical adult human contains a total of about 600 AU of DNA. Yet the DNA in each cell, only 1.5 meters in length, contains all of the information to create a new human. A clone is a new creature created from the DNA code found in a single cell.

3 DNA, coiled into a tight spiral, makes up the **chromosomes** that are the genetic material in a cell. A **gene** is a segment of a chromosome that controls a certain function. When a cell divides, each of the new cells receives a copy of the chromosomes, as genetic information is handed down to new generations.



3a To divide, a cell must duplicate its DNA. The DNA ladder splits, and new bases match to the exposed bases of the ladder to build two copies of the original DNA code. Because the base pairs almost always match correctly, errors in copying are rare. One set of the DNA code goes to each of the two new cells.

Cell Reproduction by Division



Modifying the Information

Earth's environment changes continuously. To survive, species must change as their food supply, climate, or home terrain changes. If the information stored in DNA could not change, then life would go extinct quickly. The process by which life adjusts itself to changing environments is called **biological evolution**.

When an organism reproduces, its offspring receive a copy of its DNA. Sometimes external effects such as natural radiation alter the DNA during the parent organism's lifetime, and sometimes mistakes are made in the copying process, so that occasionally the copy is slightly different from the original. Offspring born with random alterations to their DNA are called **mutants**. Most mutations make no difference, but some mutations are fatal, killing the afflicted organisms before they can reproduce. In rare but vitally important cases, a mutation can actually help an organism survive.

These changes produce variation among the members of a species. All of the squirrels in the park may look the same, but they carry a range of genetic variation. Some may have slightly longer tails or faster-growing claws. These variations make almost no difference until the environment changes. For example, if the environment becomes colder, a squirrel with a heavier coat of fur will, on average, survive longer and produce more offspring than its normal contemporaries. Likewise, the offspring that inherit this beneficial variation will also live longer and have more offspring of their own. In contrast, squirrels containing DNA recipes for thin fur coats will gradually decrease in number. These differing rates of survival and reproduction are examples of **natural selection**. Over time, the beneficial variation increases in frequency, and a species can evolve until the entire population shares the trait. In this way, natural selection adapts species to their changing environments by selecting, from the huge array of random variations, those that would most benefit the survival of the species.

It is a **Common Misconception** that evolution is random, but that is not true. The underlying mechanisms creating variation within each species may be random, but natural selection is not random because progressive changes in a species are directed by changes in the environment.

SCIENTIFIC ARGUMENT

Why is it important that errors occur in copying DNA?

Sometimes the most valuable scientific arguments are those that challenge what seems like common sense. It appears obvious that mistakes shouldn't be made in copying DNA, but in fact variation is necessary for long-term survival of a species. For example, the DNA in a starfish contains all the information the starfish needs to grow, develop, survive, and reproduce. The information must be passed on to the starfish's offspring for them to survive. That

information must change, however, if the environment changes. A change in the ocean's temperature may kill the specific shellfish that the starfish eat. If none of the starfish are able to digest another kind of food—if all the starfish have exactly the same DNA—they all will die. But if a few starfish are born with the ability to make enzymes that can digest a different kind of shellfish, the species may be able to carry on.

Variations in DNA are caused both by external factors such as natural radiation and by occasional mistakes in the copying process. The survival of life depends on this delicate balance between mostly reliable reproduction and the introduction of small variations in DNA. Now build a new argument. **Why does the DNA copying process need to be mostly reliable?**

19-2 Life in the Universe

LIFE AS WE KNOW IT consists of just the single example of life on Earth. It is OK to think of all life on Earth as being just a single type of life, because, as you learned in the previous section, all living things on Earth have the same physical basis: the same chemistry and the same genetic code alphabet. How life began on Earth and then developed and evolved into its present variety is the only solid information you have to work with, when considering what might be possible on other worlds.

Everything currently known about life on Earth indicates that the same natural processes should lead to the origin of life on some fraction of other planets with liquid water. If there is life on other worlds, does it use DNA and RNA to carry the information for life processes, or different molecules playing the same role, or some radically different scheme? There is no way to know unless another example of life is found on another world. If and when that day comes, even if the non-Earthly life is a simple one-celled organism, the discovery will be one of the most important in the history of science. It will complete the journey of human understanding, begun in the Copernican revolution, of progressive realizations that Earth is not unique.

Origin of Life on Earth

It is obvious that the 4.5 billion chemical bases that make up human DNA did not come together in the right order just by chance. The key to understanding the origin of life lies in picturing the processes of evolution running “backward.” The complex interplay of environmental factors with the DNA of generation after generation of organisms drove some life forms to become more sophisticated over time, until they became the unique and specialized creatures alive today. Imagining this process in reverse leads to the idea that life on Earth began with very simple forms.

Biologists hypothesize that the first living things would have been carbon-chain molecules able to copy themselves. Of course,

this is a scientific hypothesis for which you can seek evidence. What evidence exists regarding the origin of life on Earth?

The oldest fossils are the remains of sea creatures, and this indicates that life began in the sea. Identifying the oldest fossils is not easy, however. Ancient rocks from western Australia that are at least 3.4 billion years old contain features that biologists identify as **stromatolites**, fossilized remains of colonies of single-celled organisms (■ Figure 19-2). Fossils this old are difficult to recognize because the earliest living things did not contain easily preserved hard parts like bones or shells and because the individual organisms were microscopic. Thus the evidence, though scarce, indicates that simple organisms lived in Earth's oceans less than 1.2 billion years after Earth formed. Stromatolite colonies of microorganisms are more complex than individual cells, so

■ Figure 19-2

(a) A fossil stromatolite from western Australia that is more than 3 billion years old, constituting some of the oldest evidence of life on Earth. Stromatolites are formed, layer upon layer, by mats of bacteria living in shallow water where they are covered repeatedly by sediments. (Chip Clark, National Museum of Natural History) (b) Artist's conception of a scene on the young Earth, 3 billion years ago, with stromatolite bacterial mats growing near the shores of an ocean. (Mural by Peter Sawyer)

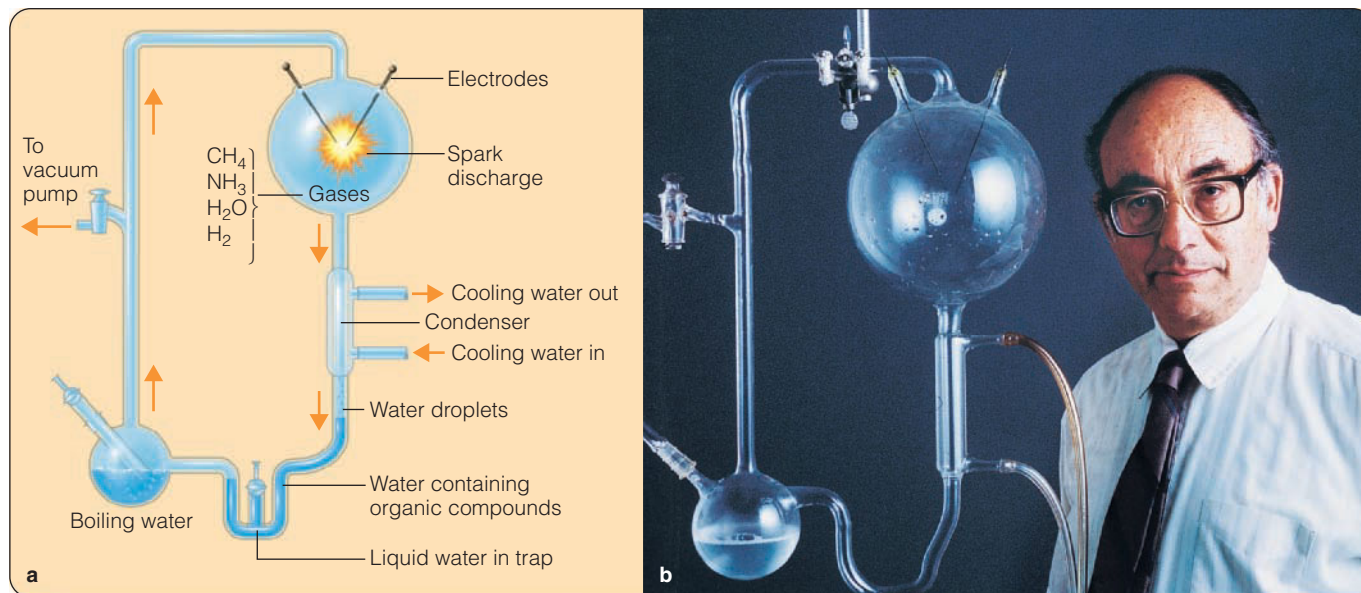
you can imagine there probably were earlier, simpler organisms. Where did those first simplest organisms come from?

An important experiment performed by Stanley Miller and Harold Urey in 1952 sought to re-create the conditions in which life on Earth began. The **Miller experiment** consisted of a sterile, sealed glass container holding water, hydrogen, ammonia, and methane. An electric arc inside the apparatus made sparks to simulate the effects of lightning in Earth's early atmosphere (■ Figure 19-3).

Miller and Urey let the experiment run for a week and then analyzed the material inside. They found that the interaction between the electric arc and the simulated atmosphere had produced many organic molecules from the raw material of the experiment, including such important building blocks of life as amino acids. (Recall that an organic molecule is simply a molecule with a carbon-chain structure and need not be derived from a living thing: "Organic" does not necessarily imply "biological.")

When the experiment was run again using different energy sources such as hot silica to represent molten lava spilling into the ocean, similar molecules were produced. Even a source of ultraviolet radiation representing the small amount of UV in sunlight was sufficient to produce complex organic molecules.





■ **Figure 19-3**

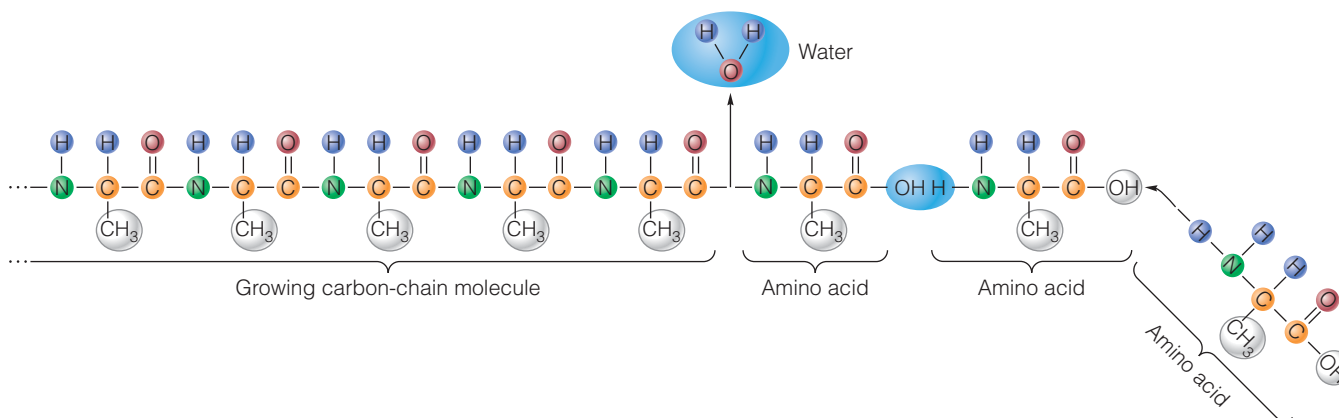
(a) The Miller experiment circulated gases through water in the presence of an electric arc. This simulation of primitive conditions on Earth produced many complex organic molecules, including amino acids, the building blocks of proteins. (b) Stanley Miller with a Miller apparatus. (Stanley Miller)

Scientists are professionally skeptical about scientific findings, and they have reevaluated the Miller–Urey experiment in light of new information. According to updated models of the formation of the solar system and Earth, Earth’s early atmosphere probably consisted mostly of carbon dioxide, nitrogen, and water vapor instead of the mix of hydrogen, ammonia, methane, and water vapor assumed by Miller and Urey. When gases corresponding to the newer understanding of the early Earth atmosphere are processed in a Miller apparatus, lesser, but still significant, amounts of organic molecules are produced.

The Miller experiment is important because it shows that complex organic molecules form naturally in a wide variety of

circumstances. Lightning, sunlight, and hot lava are just some of the energy sources that can naturally rearrange common simple molecules into the complex molecules that make life possible. If you could travel back in time, you would expect to find Earth’s early oceans filled with a rich mixture of organic compounds called the **primordial soup**.

Many of these organic compounds would have been able to link up to form larger molecules. Amino acids, for example, can link together to form proteins by joining ends and releasing a water molecule (■ Figure 19-4). That reaction, however, does not proceed easily in a water solution. Scientists hypothesize that this step may have been more likely to happen on



■ **Figure 19-4**

Amino acids can link together via the release of a water molecule to form long carbon-chain molecules. The amino acid in this hypothetical example is alanine, one of the simplest.

shorelines or in sun-warmed tidal pools where organic molecules from the primordial soup could have been concentrated by water evaporation. The production of large organic molecules may have been aided in such semidry environments by clay crystals acting as templates to hold the organic subunits close together.

These complex organic molecules were still not living things. Even though some proteins may have contained hundreds of amino acids, they did not reproduce but rather linked and broke apart at random. Because some molecules are more stable than others, and some bond together more easily than others, scientists hypothesize that a process of **chemical evolution** eventually concentrated the various smaller molecules into the most stable larger forms. Eventually, according to the hypothesis, somewhere in the oceans, after sufficient time, a molecule formed that could copy itself. At that point, the natural selection and chemical evolution of molecules became the biological evolution of living things.

An alternate theory for the origin of life holds that reproducing molecules may have arrived here from space. Astronomers have found a wide variety of organic molecules in the interstellar medium, and similar compounds have been found inside meteorites (■ Figure 19-5). The Miller experiment showed how easy



■ **Figure 19-5**

A piece of the Murchison meteorite, a carbonaceous chondrite that fell near Murchison, Australia, in 1969. Analysis of the interior of the meteorite revealed the presence of amino acids. Whether the first chemical building blocks of life on Earth originated in space is a matter of debate, but the amino acids found in meteorites illustrate how commonly amino acids and other complex organic molecules occur in the universe, even in the absence of living things. (Chip Clark, National Museum of Natural History)

it is for complex organic molecules to form naturally from simpler compounds, so it is not surprising to find them in space. Although speculation is fun, the hypothesis that life arrived on Earth from space is presently more difficult to test than the hypothesis that Earth's life originated on Earth.

Whether the first reproducing molecules formed here on Earth or in space, the important thing is that they could have formed by natural processes. Scientists know enough about those processes to feel confident about them, even though some of the steps remain unknown.

The details of the origin of the first cells are unknown. The structure of cells may have arisen automatically because of the way molecules interact during chemical evolution. If a dry mixture of amino acids is heated, the acids form long, proteinlike molecules that, when poured into water, collect to form microscopic spheres that behave in ways similar to cells (pictured in the image on the opening page to this chapter). They have a thin membrane surface, they absorb material from their surroundings, they grow in size, and they divide and bud just as cells do. However, they contain no large molecule that copies itself, so they are not alive. The first reproducing molecule to be surrounded by a protective membrane, resulting in the first cell, would have gained an important survival advantage over other reproducing molecules.

Geologic Time and the Evolution of Life

Biologists infer that the first cells must have been simple single-celled organisms similar to modern bacteria. As you learned earlier, these kinds of cells are preserved in stromatolites (Figure 19-2), mineral formations produced by layers of bacteria and shallow ocean sediments. Stromatolite fossils are found in rocks with radioactive ages of 3.4 billion years, and living stromatolites still form in some places today.

Stromatolites and other photosynthetic organisms would have begun adding oxygen, a product of photosynthesis, to Earth's early atmosphere. An oxygen abundance of only 0.1 percent would have created an ozone screen, protecting organisms from the sun's ultraviolet radiation and later allowing life to colonize the land.

Over the course of eons, the natural processes of evolution gave rise to stunningly complex **multicellular** life forms with their own widely differing ways of life. It is a **Common Misconception** to imagine that life is too complex to have evolved from such simple beginnings. It is possible because small variations can accumulate, although that accumulation requires great amounts of time.

There is little evidence of anything more than simple organisms on Earth until about 540 million years ago, almost 3 billion years after the earliest signs of life, at which time fossils indicate life suddenly developing into a wide variety of complex forms such as the trilobites (■ Figure 19-6). This sudden increase in complexity is known as the **Cambrian explosion** and marks the beginning of the Cambrian period.



■ **Figure 19-6**

(a) Trilobites made their first appearance in the Cambrian oceans. The smallest were almost microscopic, and the largest were bigger than dinner plates. This example, about the size of your hand, lived 400 million years ago in an ocean floor that is now a limestone deposit in Pennsylvania. (Franklin & Marshall College/Grundy Observatory/Michael Seeds) (b) In this artist's conception of a Cambrian sea bottom, *Anomalocaris* (near at right center and looming at upper right), about human-hand-sized, had specialized organs including eyes, coordinated fins, gripping mandibles, and a powerful, toothed maw. Notice *Opabinia* at center right with its long snout. (Smithsonian and D. W. Miller)

If you represented the entire history of Earth on a scale diagram, the Cambrian explosion would be near the top of the column, as shown at the left of ■ Figure 19-7. The emergence of most animals familiar to you today, including fishes, amphibians, reptiles, birds, and mammals, would be crammed into the top-most part of the chart, above the Cambrian explosion.

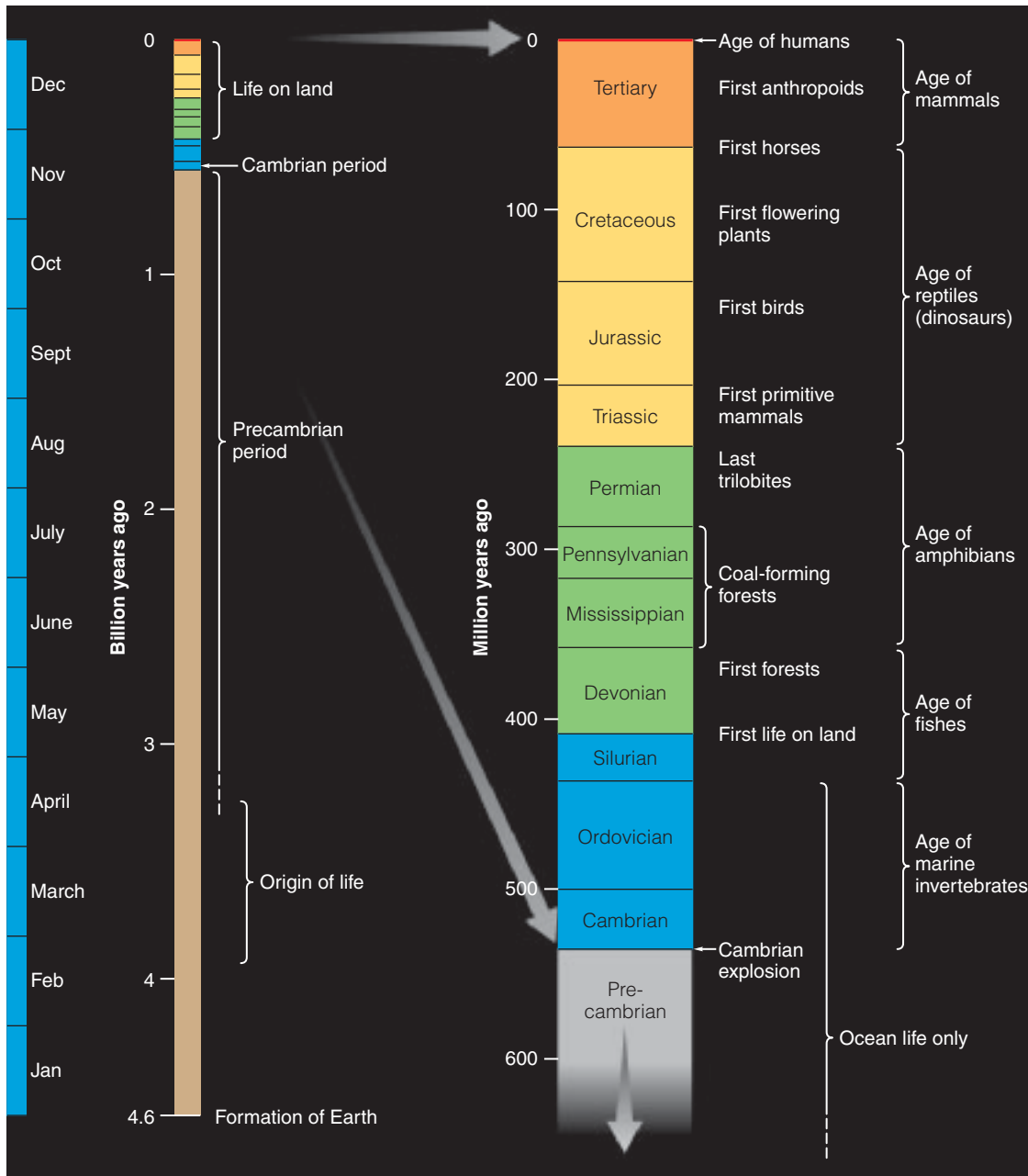
If you magnify that portion of the diagram, as shown on the right side of Figure 19-7, you can get a better idea of when these events occurred in the history of life. Humanoid creatures have walked on Earth for about 4 million years. This is a long time by the standard of a human lifetime, but it makes only a narrow red line at the top of the diagram. All of recorded history would be a microscopically thin line at the very top of the column.

To understand just how thin that line is, imagine that the entire 4.6-billion-year history of the Earth has been compressed onto a yearlong video and that you began watching this video on January 1. You would not see any signs of life until March or early April, and the slow evolution of the first simple forms would take the next six or seven months. Suddenly, in mid-November, you would see the trilobites and other complex organisms of the Cambrian explosion.

You would see no life of any kind on land until November 28, but once life appeared it would diversify quickly, and by December 12 you would see dinosaurs walking the continents. By the day after Christmas they would be gone, and mammals and birds would be on the rise.

If you watched closely, you might see the first humanoid forms by late afternoon on New Year's Eve, and by late evening you could see humans making the first stone tools. The Stone Age would last until 11:59 PM, after which the first towns, and then cities, would appear. Suddenly things would begin to happen at lightning speed. Babylon would flourish, the pyramids would rise, and Troy would fall. The Christian era would begin 14 seconds before the New Year. Rome would fall, then the Middle Ages and the Renaissance would flicker past. The American and French revolutions would occur one-and-a-half seconds before the end of the video.

By imagining the history of Earth as a yearlong video, you have gained some perspective on the rise of life. Tremendous amounts of time were needed for the first simple living things to evolve in the oceans. As life became more complex, new forms arose more and more quickly as the hardest problems—how to reproduce, how to take energy efficiently from the environment, how to move around—were “solved” by the process of biological evolution. The easier problems, like what to eat, where to live, and how to raise young, were managed in different ways by different organisms, leading to the diversity that is seen today. Intelligence—that which appears to set humans apart from other animals—may be a unique solution to an evolutionary problem posed to humanity's ancient ancestors. A smart animal is better able to escape predators, outwit its prey, and feed and shelter itself and its offspring, so under certain conditions evolution is likely to naturally select for intelligence.



■ **Figure 19-7**

Complex life has developed on Earth only recently. If the entire history of Earth were represented in a time line (left), you have to examine the end of the line closely to see details such as life leaving the oceans and dinosaurs appearing. The age of humans would still be only a thin line at the top of your diagram. If the history of Earth were a year-long videotape, humans would not appear until the last hours of December 31.

Extremophiles

Scientists on Earth are finding life in places previously judged inhospitable, such as the bottoms of ice-covered lakes in Antarctica, far underground inside solid rock, and among the cinders at the summits of extinct volcanoes (■ Figure 19-8a). An organism that can survive and even thrive in an extreme

environment is called an **extremophile**. Maybe you have friends like that.

Linguists can figure out the vocabulary of the long-vanished Indo-European language by comparing words in modern languages such as English, Spanish, Russian, Greek, and Hindi that evolved from it. In much the same way, biologists can work out the DNA sequences of ancient species by comparing the sequences of their present-day descendants. This type of analysis indicates that the creature that was ancestor to all life on Earth today resembled present-day single-celled organisms known as **archaea**, especially the extremophile types of archaea that are tolerant of high temperatures, called **thermophiles** (Figure 19-8b). Some biologists think this is evidence that life began near volcanic vents on the sea

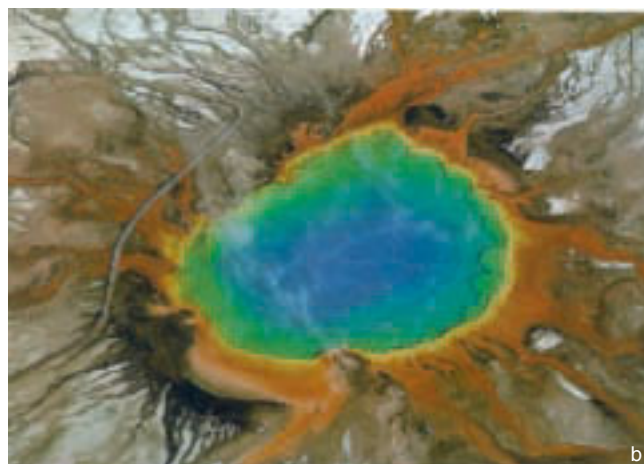


Figure 19-8

Every life form on Earth has evolved to survive in some ecological niche. (a) Wekiu bugs live with the astronomers at an altitude of 13,800 feet atop the Hawaiian volcano Mauna Kea. The bugs inhabit spaces between the icy cinders and eat insects carried up by ocean breezes. (Kris Koenig/Coast Learning Systems) (b) Grand Prismatic Spring in Yellowstone National Park is about 90 meters (300 feet) across. Colonies of thermophilic (heat-loving) single-celled organisms thrive around the edge of the pool at temperatures up to 72°C (162°F) and produce the yellow, orange, and red pigments. The water in the center of the pool is too hot even for thermophiles. (S. Leach/U. Colorado Denver)

floor or in hot rock deep underground. Others suggest that the heavy bombardment during the end of the solar system's formation would have repeatedly boiled much of Earth's oceans away. If life had already begun by then, the only organisms that survived this phase of the planet's history to become our ancestors by natural selection would have been heat resistant.

Life may have required special circumstances to start, but once it started, biological evolution allowed life to spread across Earth and adapt to a wide range of conditions. Eventually all niches—even extreme environments—became occupied. This means that, if life begins on a planet, even if most of the environment of the planet later becomes inhospitable as seems to have happened on Mars, some life could continue to survive.

It is difficult to pin down a range of environments and be sure that life cannot exist outside those conditions, so long as there is even occasionally some liquid water present. Scientists searching for life on other worlds must keep in mind Earth's extremophiles and the harsh conditions in which they thrive.

Life in Our Solar System

Could there be carbon-based life elsewhere in our solar system? Liquid water seems to be a requirement of carbon-based life, necessary both as the medium for vital chemical reactions and to transport nutrients and wastes. It is not surprising that life developed in Earth's oceans and stayed there for billions of years before it was able to colonize the land.

Scientists are in general agreement that any world harboring living things must have significant quantities of some type of liquid as the medium in which the processes of life can occur.

Water is a cosmically abundant substance with properties such as high heat capacity that set it apart from other common molecules that are liquid at the temperatures of planetary surfaces. Maybe there are other liquids that can support the processes of life on other planets, but water, aside from being common in the universe, has characteristics that cause Earth scientists to regard it as special, and not just because they are made of water themselves.

Many worlds in the solar system can be eliminated immediately as hosts for water-based life because liquid water is not possible there. The moon and Mercury are airless, and water would boil away into space immediately. Venus has traces of water vapor in its atmosphere, but it is too hot for liquid water to survive on the surface. The Jovian planets have deep atmospheres, and at certain altitudes it is likely that water condenses into liquid droplets. However, it seems unlikely that life could have originated there. The Jovian planets do not have solid surfaces, so isolated water droplets cannot mingle to mimic the rich primordial oceans of Earth, where organic molecules grew and interacted. Additionally, powerful downdraft currents in the atmospheres of the giant planets would quickly carry any reproducing molecules that did form there into inhospitably hot lower regions.

At least one of the Jovian satellites could potentially support life. Jupiter's moon Europa appears to have a liquid-water ocean below its icy crust, and minerals dissolved in the water could provide a source of raw material for chemical evolution. Europa's ocean is kept warm and liquid now by tidal heating. There also may be liquid water layers under the surfaces of

Ganymede and Callisto. That can change as the moons interact gravitationally and their orbits vary; Europa, Ganymede, and Callisto may have been frozen solid at other times in their histories, which would probably have destroyed any living organism that had developed there.

Saturn's moon Titan is rich in organic molecules. Sunlight converts the methane in Titan's atmosphere into organic smog particles that settle to the surface. The chemistry of life that could have evolved from those molecules and survived in Titan's lakes of methane is unknown. It is fascinating to consider possibilities, but Titan's extremely low temperature of -180°C (-290°F) would make chemical reactions so slow that life processes seem unlikely.

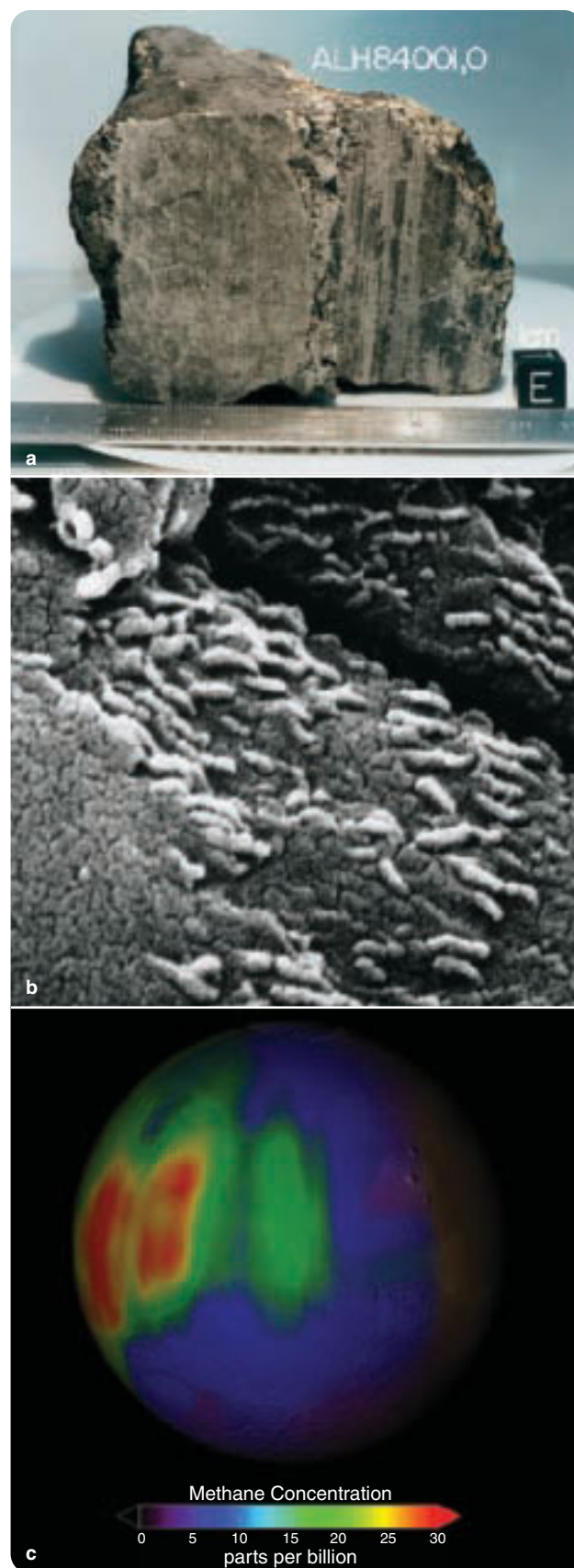
Water containing organic molecules has been observed venting from the south polar region of Saturn's moon Enceladus. It is possible that life could exist in that water under Enceladus's crust, but the moon is very small, and its tidal heating might operate only occasionally. Enceladus may not have had plentiful liquid water for the extended time necessary for the rise of life.

Mars is the most likely place for life to exist in the solar system because there is a great deal of evidence that liquid water once flowed on its surface. Even so, results from searches for signs of life on Mars are not encouraging. The robotic spacecraft Viking 1 and Viking 2 landed on Mars in 1976 and tested soil samples for living organisms. Some of the tests had puzzling semipositive results that scientists hypothesize were caused by nonbiological chemical reactions in the soil. No evidence clearly indicates the presence of life or even of organic molecules currently in the Martian soil. If life survives on Mars, it may be hidden below ground where there may be liquid water and where UV radiation from the sun cannot penetrate.

There was a splash of news stories in the 1990s regarding supposed chemical and physical traces of life on Mars discovered inside a Martian meteorite found in Antarctica (■ Figure 19-9). Scientists were excited by the announcement, but they employed professional skepticism and immediately began testing the evidence. Their results suggest that the unusual chemical signatures in the rock may have formed by processes that did not involve life. Tiny features in the rock that were originally thought to be

■ Figure 19-9

(a) Meteorite ALH84001 is one of a dozen meteorites known to have originated on Mars. Its name means this meteorite was the first one found in 1984 near Antarctica's Allan Hills. (b) A research group claimed that the meteorite contained chemical and physical traces of ancient life on Mars, including what appear to be fossils of microscopic organisms. That evidence has not been confirmed, and the claim continues to be tested and debated. (NASA) (c) A map of Mars color-coded to show methane concentration in the atmosphere measured by spectrographs on Earth-based telescopes. Methane is most abundant in locations apart from volcanic regions, indicating the methane may be produced biologically. (NASA / M. Mumma)



fossils of ancient Martian microorganisms could possibly be non-biological mineral formations instead.

In 2009 astronomers observing the Martian atmosphere announced detection of faint traces of methane, a substance made abundantly by living things on Earth. Methane would be destroyed in the Martian environment by solar UV radiation and chemical reactions, so the methane that is present must have been produced recently. There are also geological processes that can emit methane, but those processes are connected with volcanism. The map of Martian atmospheric methane concentrations in Figure 19-9c shows methane primarily in locations that are not volcanic provinces. Perhaps organisms living in the Martian soil are making methane right now. This evidence regarding potential life on Mars remains highly controversial. Conclusive evidence of life on Mars may have to wait until a geologist from Earth can scramble down dry Martian streambeds and crack open rocks looking for fossils, or drill into the soil seeking signs of metabolizing microorganisms.

There is no strong evidence for the existence of life in the solar system other than on Earth. Now your search will take you to distant planetary systems.

Life in Other Planetary Systems

Could life exist in other planetary systems? You already know that there are many different kinds of stars and that many of these stars have planetary systems. As a first step toward answering this question, you can try to identify the kinds of stars that seem most likely to have stable planetary systems where life could evolve.

If a planet is to be a suitable home for living things, it must be in a stable orbit around its sun. That is easy in a planetary system like our own, but planet orbits in binary star systems would be unstable unless the component stars are very close together or very far apart. Astronomers can calculate that, in binary systems with stars separated by intermediate distances of a few AU, the planets should eventually be swallowed up by one of the stars or ejected from the system. Half the stars in the galaxy are members of binary systems, and many of them are unlikely to support life on planets.

Moreover, just because a star is single does not necessarily make it a good candidate for sustaining life. Earth required perhaps as much as 1 billion years to produce the first cells and 4.6 billion years for intelligence to emerge. Massive stars that shine for only a few million years do not meet this criterion. If the history of life on Earth is representative, then stars more massive and luminous than about spectral type F5 last too short a time for complex life to develop. Main-sequence stars of types G and K, and possibly some of the M stars, are the best candidates.

The temperature of a planet is also important, and that depends on the type of star it orbits and its distance from the star. Astronomers have defined a **habitable zone** around a star as a

region within which orbiting planets have temperatures permitting the existence of liquid water. The sun's habitable zone extends from near the orbit of Venus to the orbit of Mars, with Earth right in the middle. A low-luminosity star has a small and narrow habitable zone, whereas a high-luminosity star has a large and wide one.

Stable planets inside the habitable zones of long-lived stars are the places where life seems most likely, but, given the tenacity and resilience of Earth's life forms, there might be other, seemingly inhospitable, places in the universe where life exists. You should also note that three of the environments considered as possible havens for life—Europa, Titan, and Enceladus—are in the outer solar system, far outside the sun's conventionally defined habitable zone.

SCIENTIFIC ARGUMENT

What evidence indicates that life is possible on other worlds?

A good scientific argument involves careful analysis of evidence. Fossils on Earth show that life originated in the oceans at least 3.4 billion years ago, and biologists have outlined likely chemical processes that, over long time intervals, could have changed simple organic compounds into reproducing molecules inside membranes, the first simple life forms. Meager fossil evidence indicates that life developed slowly at first. The pace of evolution quickened about half a billion years ago, when life took on complex forms. Later, life emerged onto the land and continued evolving rapidly into diverse forms. Intelligence is a relatively recent development: It is only a few million years old.

If this evolutionary process occurred on Earth, it seems reasonable that it could have occurred on other worlds as well. Earth-like worlds could be plentiful in the universe. Life may begin and eventually evolve to intelligence on any world where conditions are right. Now make a related argument. **What are the conditions you should expect on other worlds that host life?**

19-3 Intelligent Life in the Universe

COULD INTELLIGENT LIFE ARISE ON other worlds? To try to answer this question, you can estimate the chances of any type of life arising on other worlds, then assess the likelihood of that life developing intelligence. If other civilizations exist, it is possible humans eventually may be able to communicate with them. Nature puts restrictions on the pace of such conversations, but the main problem lies in the unknown life expectancy of civilizations.

Travel Between the Stars

The distances between stars are almost beyond comprehension. The fastest human device ever launched, the *New Horizons* probe currently on its way to Pluto and the Kuiper belt, will take about 90,000 years to travel the distance to the nearest star, 4 light-years.

The obvious way to overcome these huge distances is with tremendously fast spaceships, but even the closest stars are many light-years away.

Nothing can exceed the speed of light, and accelerating a spaceship close to the speed of light takes huge amounts of energy. Even if you travel slower than light, your rocket would still require massive amounts of fuel. If you wanted to pilot a spaceship with a mass of 100 tons (about the size of a fancy yacht) to the nearest star, and you traveled at half the speed of light so as to arrive in eight years, the trip would require 400 times as much energy as the entire United States consumes in a year. Don't even think about how much fuel the starship *Enterprise* needs.

These limitations not only make it difficult for humans to leave the solar system, but they would also make it difficult for aliens to visit Earth. Reputable scientists have studied “unidentified flying objects” (UFOs) and have never found any evidence that Earth is being visited or has ever been visited by aliens (**How Do We Know? 19-2**). Humans are unlikely ever to meet aliens face-to-face. However, communication by electromagnetic signals across interstellar distances takes relatively little energy.

Radio Communication

Nature puts restrictions on travel through space, and it also restricts the possibility of communicating with distant civilizations by radio. One restriction is based on simple physics: Radio signals are electromagnetic waves and travel at the speed of light. Due to the distances between the stars, the speed of radio waves would severely limit humanity's ability to carry on normal conversations with distant civilizations. Decades could elapse between asking a question and getting an answer.

So, rather than try to begin a conversation, one group of astronomers decided in 1974 to broadcast a message of greeting toward the globular cluster M13, 26,000 light years away, using the Arecibo radio telescope. When the signal arrives 26,000 years in the future, alien astronomers may be able to understand it because the message is **antcoded**, meaning that it is intended to be decoded by beings about whom we know nothing except that they build radio telescopes. The message is a string of 1679 pulses and gaps. Pulses represent 1s, and gaps represent 0s. The string can be arranged in two dimensions in only two possible ways: as 23 rows of 73 or as 73 rows of 23. The second arrangement forms a picture containing information about life on Earth (■ Figure 19-10).

What are the chances that a signal like the Arecibo message would be heard across interstellar distances? Surprisingly, a radio dish the size of the Arecibo telescope, located anywhere in the Milky Way Galaxy, could detect the output from “our” Arecibo. The human race's modest technical capabilities already can put us into cosmic chat rooms.

Although the 1974 Arecibo beacon was the only powerful signal sent purposely from Earth to other star systems, Earth is sending out many other signals more or less accidentally. Short-wave radio signals, including TV and FM, have been leaking into space for the last 60 years or so. Any civilization within 60 light-years could already have detected Earth's civilization. That works both ways: Alien signals, whether intentional messages of friendship or the blather of their equivalent to daytime TV, could be arriving at Earth now. Groups of astronomers from several countries are pointing radio telescopes at the most likely stars and listening for alien civilizations.

Which channels should astronomers monitor? Signals with wavelengths longer than 100 cm would get lost in the background noise of our Milky Way Galaxy, while wavelengths shorter than about 1 cm are mostly absorbed in Earth's atmosphere. Between those wavelengths is a radio window that is open for communication. Even this restricted window contains millions of possible radio-frequency bands and is too wide to monitor easily, but astronomers may have thought of a way to narrow the search. Within this broad radio window lie the 21-cm spectral line of neutral hydrogen and the 18-cm line of OH (■ Figure 19-11). The interval between those lines has low background interference and is named the **water hole** because H plus OH yields water. Any civilizations sophisticated enough to do radio astronomy would know of these lines and might appreciate their significance in the same way as do Earthlings.

A number of searches for extraterrestrial radio signals have been made, and some are now under way. This field of study is known as **SETI, Search for Extra-Terrestrial Intelligence**, and it has generated heated debate among astronomers, philosophers, theologians, and politicians. You might imagine that the discovery of real alien intelligence would cause a huge change in humanity's worldview, akin to Galileo's discovery that the moons of Jupiter do not go around the Earth. Congress funded a NASA SETI search for a short time but ended support in the early 1990s. In fact, the annual cost of a major search is only about as much as a single Air Force helicopter, but much of the reluctance to fund searches stems from issues other than cost. Segments of the population, including some members of Congress, considered the idea of extraterrestrial beings as so outlandish that continued public funding for the search became impossible.

In spite of the controversy, the search continues. The NASA SETI project canceled by Congress was renamed Project Phoenix and completed using private funds. The SETI Institute, founded in 1984, managed Project Phoenix plus several other important searches and is currently building a new radio telescope array in northern California, in collaboration with the University of California, Berkeley, and partly funded by Paul Allen of Microsoft (■ Figure 19-12).

There is even a way for you to help with searches. The Berkeley SETI team (*Note: they are separate from the SETI Institute*), with the support of the Planetary Society, has

UFOs and Space Aliens

Has Earth been visited by aliens? If you conclude that there is likely to be life on other worlds, then you might be tempted to use UFO sightings as evidence to test your hypothesis. Scientists don't do this for two reasons.

First, the reputation of UFO sightings and alien encounters does not inspire confidence that these data are reliable. Most people hear of such events in grocery store tabloids, daytime talk shows, or sensational "specials" on viewer-hungry cable networks. You should take note of the low reputation of the media that report UFOs and space aliens. Most of these reports, like the reports that Elvis is alive and well, are simply made up for the sake of sensation, and you cannot use them as reliable evidence.

Second, the few UFO sightings that are not made up do not survive careful examination. Most are mistakes and unintentional

misinterpretations, committed by honest people, of natural events or human-made objects. It is very important to realize that experts have studied these incidents over many decades and found *none* that are convincing to the professional scientific community. In short, despite false claims to the contrary on TV shows, there is no dependable evidence that Earth has ever been visited by aliens.

In a way, that's too bad. A confirmed visit by intelligent creatures from beyond our solar system would answer many questions. It would be exciting, enlightening, and, like any real adventure, a bit scary. Most scientists would love to be part of such a discovery. But, scientists must professionally pay attention to what is supported by evidence rather than what might be thrilling. There is not yet any direct evidence of life on other worlds.



Flying saucers from space are fun to think about, but there is no evidence that they are real.

recruited about 4 million owners of personal computers that are connected to the Internet. You can download a screen saver that searches data files from the Arecibo radio telescope for signals whenever you are not using the computer. For information, locate the *seti@home* project at <http://setiathome.ssl.berkeley.edu/>.

The search continues, but radio astronomers struggle to hear anything against the worsening babble of radio noise from human civilization. Wider and wider sections of the electromagnetic spectrum are being used for Earthly communication, and this, combined with stray electromagnetic radiation from electronic devices including everything from computers to refrigerators, makes hearing faint radio signals difficult. It would be ironic if humans fail to detect faint radio signals from another world because our own world has become too noisy. One alternate search strategy is to look for rapid flashes of laser light at optical or near-infrared wavelengths. Such extraterrestrial signals, if they exist, would have the advantage of being easily distinguished from natural light sources but the disadvantage of being blocked by interstellar dust. Ultimately, the chance of success for any of the searches depends on the number of inhabited worlds in the galaxy.

How Many Inhabited Worlds?

Given enough time, the searches will find other worlds with civilizations, assuming that there are at least a few out there. If intelligence is common, scientists should find signals relatively soon—within the next few decades—but if intelligence is rare, it may take much longer.

Simple arithmetic can give you an estimate of the number of technological civilizations in the Milky Way Galaxy with which you might communicate, N_c . The formula proposed for discussions about N_c is named the **Drake equation** after the radio astronomer Frank Drake, a pioneer in the search for extraterrestrial intelligence. The version of the Drake equation presented here is modified slightly from its original form:

$$N_c = N_* \cdot f_p \cdot n_{\text{HZ}} \cdot f_L \cdot f_I \cdot f_S$$

N_* is the number of stars in our galaxy, and f_p represents the fraction of stars that have planets. If all single stars have planets, f_p is about 0.5. The factor n_{HZ} is the average number of planets in each planetary system suitably located in the habitable zone—meaning, for the sake of the present discussion, the number of planets per planetary system possessing substantial amounts of liquid water. The conventional habitable zone in our system

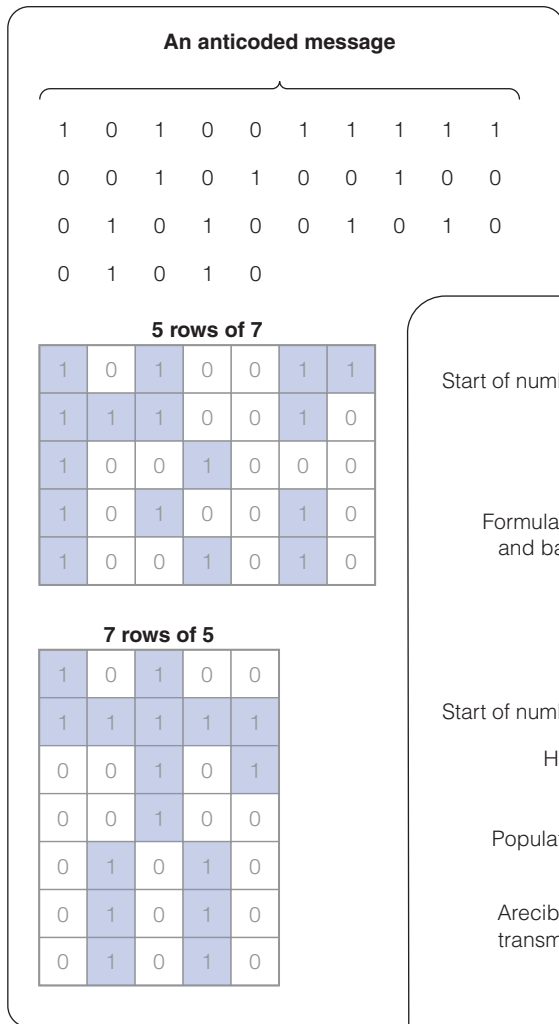


Figure 19-10

(a) An anticoded message is designed for easy decoding. Here a string of 35 radio pulses, represented as 1s and 0s, can be arranged in only two ways, as 5 rows of 7 or 7 rows of 5. The second way produces a friendly message. (b) The Arecibo message describes life on Earth (color added for clarity). Binary numbers give the height of the human figure (1110) and the diameter of the telescope dish (100101111110) in units of the wavelength of the signal, 12.3 cm. (NASA)

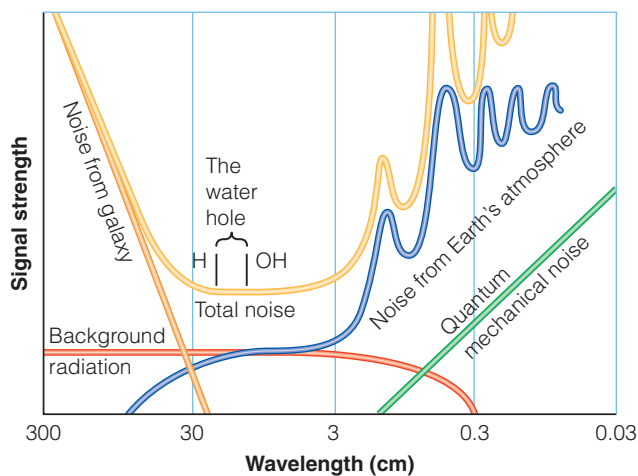
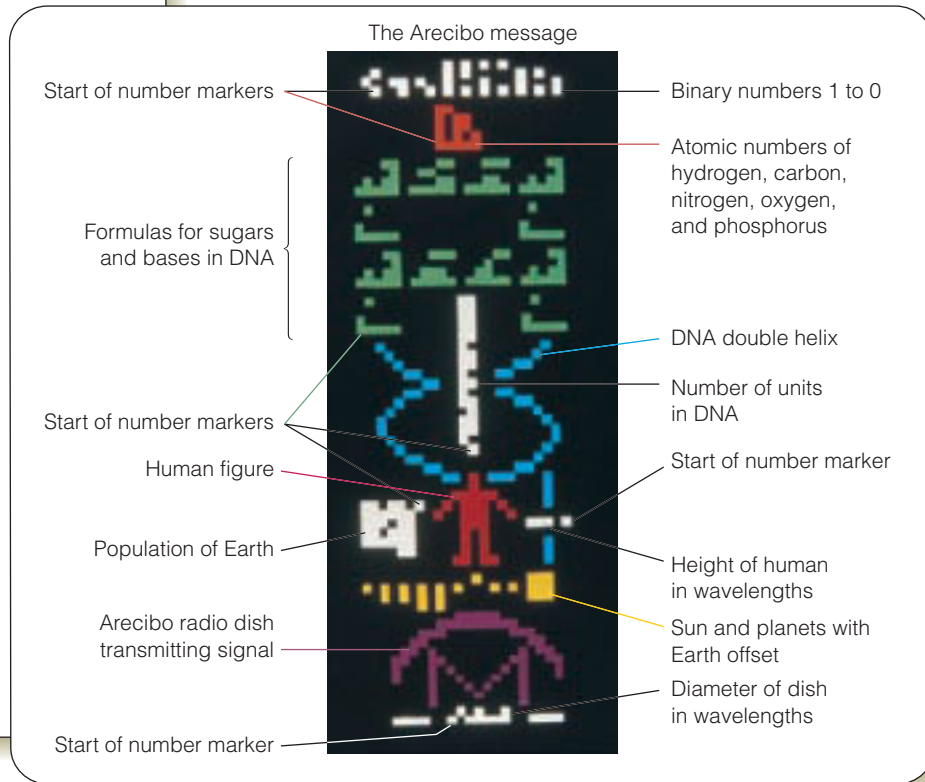


Figure 19-11

Radio noise from various astronomical sources and Earth's atmospheric opacity make it difficult to detect distant signals at wavelengths longer than 100 cm or shorter than 1 cm. In this range, wavelengths of radio emission lines from H atoms and from OH molecules mark a small wavelength range named the water hole that may be a likely channel for interstellar communication.

contains Earth's orbit, and, arguably, Venus and Mars as well. Europa and Enceladus in our solar system show that liquid water can exist due to tidal heating outside the conventional habitable zone. Thus, n_{HZ} may be larger than had been originally thought. The factor f_L is the fraction of suitable planets on which life begins, and f_I is the fraction of those planets where life evolves to intelligence.

The six factors on the right-hand side of the Drake equation can be roughly estimated, with decreasing certainty as you proceed from left to right. The final factor is extremely uncertain. That factor f_S is the fraction of a star's life during which an intelligent species is communicative. If a society survives at a technological level for only 100 years, the chances of communicating with it are small. On the other hand, a society that stabilizes and remains technologically capable for a long time is much more



■ **Figure 19-12**

Part of the Allen Telescope Array (ATA), which is now being built in California, is planned to eventually include 350 radio dishes, each 6 meters in diameter, in an arrangement designed to maximize their combined angular resolution. As radio astronomers aim the telescope at galaxies and nebulae of scientific interest, state-of-the-art computer systems will analyze stars in the field of view searching for signals from distant civilizations. (SETI Institute)

likely to be detected. For a star with a life span of 10 billion years, f_s might conceivably range from 10^{-8} for extremely short-lived societies to 10^{-4} for societies that survive for a million years. ■ Table 19-1 summarizes what many scientists consider a reasonable range of values for f_s and the other factors.

If the optimistic estimates are true, there could be a communicative civilization within a few tens of light-years from Earth. On the other hand, if the pessimistic estimates are true, Earth may be the only planet that is capable of communication within thousands of the nearest galaxies.

■ **Table 19-1** | **The Number of Technological Civilizations per Galaxy**

Estimates	Variables	Pessimistic	Optimistic
N_*	Number of stars per galaxy	2×10^{11}	2×10^{11}
f_p	Fraction of stars with planets	0.1	0.5
n_{HZ}	Number of planets per star that lie in habitable zone for longer than 4 billion years	0.01	1
f_L	Fraction of suitable planets on which life begins	0.01	1
f_I	Fraction of planets with life where life evolves to intelligence	0.01	1
f_S	Fraction of star's existence during which a technological society survives	10^{-8}	10^{-4}
N_c	Number of communicative civilizations per galaxy	2×10^{-4}	1×10^7

SCIENTIFIC ARGUMENT

Why does the number of civilizations that could be detected depend on how long civilizations survive at a technological level?

This scientific argument depends on the timing of events. If you turned a radio telescope to the sky and scanned millions of frequency bands for many stars, you would be taking a snapshot of the universe at a particular time. Broadcasts from other civilizations must be arriving at that same time if they are to be detected. If most civilizations survive for a long time, there is a much greater chance that you will detect one of them in your snapshot than if

civilizations tend to disappear quickly due to, for example, nuclear war or environmental collapse. If most civilizations last only a short time, there may be none capable of transmitting during the cosmically short interval when Earthlings are capable of building radio telescopes to listen for them.

The speed at which astronomers can search for signals is limited because computers must search many frequency intervals, but not all frequencies inside Earth's radio window are subject to intensive search. Build a new argument to explain: **Why is the water hole an especially good frequency band in which to listen?**

What Are We? Matter and Spirit

There are over 4000 religions around the world, and nearly all hold that humans have a dual nature: We are physical objects made of atoms, but we are also spiritual beings. Science is unable to examine the spiritual side of existence, but it can tell us about our physical nature.

The matter you are made of appeared in the big bang and was cooked into a wide range of elements inside stars. Your atoms may have been inside at least two or three generations of stars. Eventually, your atoms became part of a nebula that contracted to form our sun and the planets of the solar system.

Your atoms have been part of Earth for the last 4.6 billion years. They have been recycled many times through dinosaurs,

stromatolites, fish, bacteria, grass, birds, worms, and other living things. You are using your atoms now, but when you are done with them, they will go back to Earth and be used again and again.

When the sun swells into a red giant star and dies in a few billion years, Earth's atmosphere and oceans will be driven away, and at least the outer few kilometers of Earth's crust will be vaporized and blown outward to become part of the nebula around the white-dwarf remains of the sun. Your atoms are destined to return to the interstellar medium and will become part of future generations of stars and planets.

The message of astronomy is that humans are not just observers: We are participants in the universe. Among all of

the galaxies, stars, planets, planetesimals, and bits of matter, humans are objects that can think, and that means we can understand what we are.

Is the human race the only thinking species? If so, we bear the sole responsibility to understand and admire the universe. The detection of signals from another civilization would demonstrate that we are not alone, and such communication would end the self-centered isolation of humanity and stimulate a reevaluation of the meaning of human existence. We may never realize our full potential as humans until we communicate with non-human intelligent life.

Study and Review

Summary

- ▶ Consideration of the possibility that life exists elsewhere in the universe, and the study of life and its origin on Earth as it relates to life on other worlds, is called **astrobiology** (p. 398).
- ▶ Life can be defined as a process that extracts energy from the surroundings, maintains an organism, and modifies the surroundings to promote the organism's survival.
- ▶ Living things have a physical basis—the arrangement of matter and energy that makes life possible. Life on Earth is based on carbon chemistry occurring in bags of water (cells).
- ▶ Living things must have a controlling unit of information that can be passed to successive generations.
- ▶ Genetic information for life on Earth is stored in long carbon-chain molecules such as **DNA (deoxyribonucleic acid)** (p. 400).
- ▶ The DNA molecule stores information in the form of chemical bases linked together like the rungs of a ladder. Copied by the **RNA (ribonucleic acid)** (p. 401) molecule, the patterns of bases act as recipes for connecting together **amino acid** (p. 400) subunits to construct **proteins** (p. 400), including **enzymes** (p. 400) that are respectively the main structural and control components of the life process.

- ▶ The unit of heredity is a **gene (p. 401)**, a piece or several pieces of DNA that in most cases specifies the construction of one particular type of protein molecule. Genes are connected together in structures called **chromosomes (p. 401)**, that are essentially single long DNA molecules.
- ▶ When a cell divides, the chromosomes split lengthwise and duplicate themselves so that each of the new cells can receive a copy of the genetic information.
- ▶ **Biological evolution (p. 402)** is the process by which life adjusts itself to changing environments.
- ▶ Errors in duplication or damage to the DNA molecule can produce **mutants (p. 402)**, organisms that contain new DNA information and therefore have new properties. Variation in genetic codes can become widespread among individuals in a species. **Natural selection (p. 402)** determines which of these variations are best suited to survive, and the species evolves to fit its environment.
- ▶ Evolution is not random. Genetic variation is random, but natural selection is controlled by the environment.
- ▶ The oldest definitely identified fossils on Earth, structures called **stromatolites (p. 403)** that are composed of stacks of bacterial mats and sediment layers, are at least 3.4 billion years old. Those fossils provide evidence that life began in the oceans.
- ▶ Fossil evidence indicates that life began on Earth as simple single-celled organisms like bacteria and much later evolved into more complex, **multicellular (p. 405)** creatures.
- ▶ The **Miller experiment (p. 403)** shows that the chemical building blocks of life form naturally under a wide range of circumstances.
- ▶ Scientists hypothesize that **chemical evolution (p. 405)** occurred before biological evolution. Chemical evolution concentrated simple molecules into a diversity of larger stable organic molecules dissolved in the young Earth's oceans, but those molecules did not reproduce copies of themselves. The hypothetical organic-rich water is sometimes referred to as the **primordial soup (p. 404)**. Biological evolution began when molecules developed the ability to make copies of themselves.
- ▶ Life forms did not become large and complex until about 0.5 billion years ago, during what is called the **Cambrian explosion (p. 405)**.
- ▶ Life emerged from the oceans only about 0.4 billion years ago, and human intelligence developed over the last 4 million (0.004 billion) years.
- ▶ Life as it is known on Earth requires liquid water and thus a specific range of temperatures.
- ▶ Organisms that thrive in extreme environments are called **extremophiles (p. 407)**. Genetic evidence indicates that the common ancestor of all Earth life was a **thermophile (p. 407)**, a heat-tolerant version of present-day single-celled organisms called **archaea (p. 407)**.
- ▶ No other planet in our solar system appears to harbor life at present. Most are too hot or too cold, although life might have begun on Mars before the planet became too cold and dry. If so, life conceivably could persist today on Mars in limited hospitable environments.
- ▶ Liquid water exists, and therefore Earth-like life is at least possible, under the surfaces of Jupiter's moons Europa and Ganymede and Saturn's moon Enceladus. Saturn's moon Titan has abundant organic compounds but does not have liquid water.
- ▶ Because the origin of life and its evolution into intelligent creatures took so long on Earth, scientists do not consider middle- and upper-main-sequence stars, which shine for astronomically short time spans, as likely hosts for life-bearing planets.
- ▶ Main-sequence G and K stars are thought to be likely candidates to host planets with life. Scientists are not sure whether the M stars are also good candidates.
- ▶ The **habitable zone (p. 410)** around a star, within which planets can have liquid water on their surfaces, may be larger than scientists had

expected, given the wide variety of living things now found in extreme environments on Earth. Tidally heated moons orbiting large planets could have liquid water at any distance from a star.

- ▶ Because of distance, speed, and fuel, travel between the stars seems almost impossible for humans or for aliens who might visit Earth.
- ▶ Communication between planetary systems using electromagnetic signals such as radio waves or laser beams may be possible, but a real conversation would be difficult because of long travel times for such signals.
- ▶ Broadcasting a radio (or light) beacon of pulses would distinguish the signal from naturally occurring emission and identify the source as a technological civilization. The signal can be **anticoiled (p. 411)** in the hope it would be possible for another civilization to decode.
- ▶ One good part of the radio spectrum for communication is called the **water hole (p. 411)**, the wavelength range from the 21-cm spectral line of hydrogen to the 18-cm line of OH. Even so, millions of radio wavelengths need to be tested to fully survey the water hole for a given target star.
- ▶ Sophisticated searches are now underway to detect radio transmissions from civilizations on other worlds, but such **SETI (Search for Extra-Terrestrial Intelligence) (p. 411)** programs are hampered by limited computer power and radio noise pollution from human civilization.
- ▶ The number of civilizations in our galaxy that are at a technological level and able to communicate while humans are listening can be estimated by the **Drake equation (p. 412)**. This number is limited primarily by the lifetimes of their and our civilizations.

Review Questions

1. If life is based on information, what is that information?
2. How does the DNA molecule produce a copy of itself?
3. What would happen to a life form if the genetic information handed down to offspring was copied extremely inaccurately? How would that endanger the future of the life form?
4. What would happen to a life form if the information handed down to offspring was always the same? How would that endanger the future of the life form?
5. Give an example of natural selection acting on new DNA patterns to select the most advantageous characteristics.
6. What evidence do scientists have that life on Earth began in the sea?
7. Why do scientists generally think that liquid water is necessary for the origin of life?
8. What is the difference between chemical evolution and biological evolution?
9. What is the significance of the Miller experiment?
10. How does intelligence make a creature more likely to survive?
11. Why are upper-main-sequence (high-luminosity) stars unlikely sites for intelligent civilizations?
12. Why is it reasonable to suspect that travel between stars is nearly impossible?
13. How does the stability of technological civilizations affect the probability that Earth can communicate with them?
14. What is the water hole, and why is it a good "place" to search for extraterrestrial civilizations?
15. Why is it difficult to anticode a message? In other words, why is it hard to make a message that potentially can be understood by completely unknown recipients?
16. **How Do We Know?** How do science and religion have complementary explanations of the world?
17. **How Do We Know?** Why are scientists sure Earth has never been visited by aliens?

Discussion Questions

1. Do you expect that hypothetical alien recipients of the Arecibo message will be able to decode it? Why or why not?
2. How do you think the detection of extraterrestrial intelligence would be received by the public? Would it be likelier to upset, or confirm, human's beliefs about themselves and the world?
3. What do you think it would mean if decades of careful searches for radio signals for extraterrestrial intelligence turn up nothing?

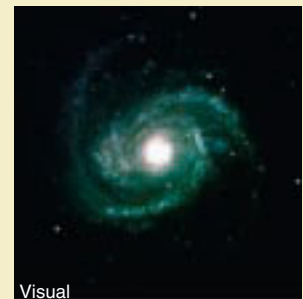
Problems

1. A single human cell encloses about 1.5 m of DNA, containing 4.5 billion base pairs. What is the spacing between these base pairs in nanometers? That is, how far apart are the rungs on the DNA ladder?
2. If you represent Earth's history by a line 1 m long, how long a segment would represent the 400 million years since life moved onto the land? How long a segment would represent the 4-million-year history of human life?
3. If a human generation, the average time from birth to childbearing, has been 20 years long, how many generations have passed in the last 1 million years?
4. If a star must remain on the main sequence for at least 4 billion years for life to evolve to intelligence, what is the most massive a star can be and still possibly harbor intelligent life on one of its planets? (*Hints:* See Chapter 12 and Appendix Table A-7.)
5. If there are about 1.4×10^{-4} stars like the sun per cubic light-year, how many lie within 100 light-years of Earth? (*Hint:* The volume of a sphere is $\frac{4}{3}\pi r^3$.)
6. Mathematician Karl Gauss suggested planting forests and fields in gigantic geometric figures as signals to possible Martians that intelligent life exists on Earth. If Martians had telescopes that could resolve details no smaller than 1 arc second, how large would the smallest element of Gauss's signal have to be for it to be visible at Mars's closest approach to Earth? (*Hints:* See Appendix Table A-10 and use the small-angle formula, Chapter 3.)

7. If you detected radio signals with an average wavelength of 20 cm and suspected that they came from a civilization on a distant Earth-like planet, roughly how much of a change in wavelength should you expect to see because of the orbital motion of the distant planet? (*Hints:* See the equation for the Doppler effect in Chapter 7; the Earth's orbital velocity is 30 km/s.)
8. Calculate the number of communicative civilizations per galaxy using your own estimates of the factors in Table 19-1.

Learning to Look

1. The star cluster shown in the image to the right contains cool red giants and main-sequence stars from hot blue stars all the way down to red dwarfs. Discuss the likelihood that planets orbiting any of these stars might be home to life. (*Hint:* Estimate the age of the cluster.)
2. If you could search for life in the galaxy shown in the image to the right, would you look among disk stars or halo stars? Discuss the factors that influence your decision.



Afterword



The aggregate of all our joys and sufferings, thousands of confident religions, ideologies and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilizations, every king and peasant, every young couple in love, every hopeful child, every mother and father, every inventor and explorer, every teacher of morals, every corrupt politician, every superstar, every supreme leader, every saint and sinner in the history of our species, lived there on a mote of dust, suspended in a sunbeam.

CARL SAGAN (1934–1996)

Earth photographed by Voyager 1 from the edge of the solar system.
(NASA)

OUR JOURNEY TOGETHER IS OVER; but, before we part company, let's ponder one final time the primary theme of this book—humanity's place in the physical universe. Astronomy gives us some comprehension of the workings of stars, galaxies, and planets, but its greatest value lies in what it teaches us about ourselves. Now that you have surveyed astronomical knowledge, you can better understand your own position in nature.

To some, the word *nature* conjures up visions of furry rabbits hopping about in a forest glade. To others, nature is the blue-green ocean depths, and still others think of nature as windswept mountaintops. As diverse as these images are, they are all Earth-bound. Having studied astronomy, you can see nature as a beautiful mechanism composed of matter and energy, interacting according to simple rules, forming galaxies, stars, planets, mountaintops, ocean depths, forest glades, and people.

Perhaps the most important astronomical lesson is that humanity is a small but important part of the universe. Most of the universe is probably lifeless. The vast reaches between the galaxies appear to be empty of all but the thinnest gas, and stars are much too hot to preserve the chemical bonds that seem necessary for life to survive and develop. It seems that only on the surfaces of a few planets, where temperatures are moderate, can atoms link together in special ways to form living matter.

If life is special, then intelligence is precious. The universe must contain many planets devoid of life, planets where sunlight has shined unfelt for billions of years. There may also exist planets on which life has developed but has not become complex, planets where the wind stirs wide plains of grass and rustles through dark forests. On some planets, creatures resembling Earth's insects, fish, birds, and animals may watch the passing days only dimly aware of their own existence. It is intelligence, human or alien, that gives meaning to the landscape.

Science is the process by which Earth's intelligence has tried to understand the physical universe. Science is not the invention of new devices or processes. It does not create home computers, cure the mumps, or manufacture plastic spoons—those are engineering and technology, the adaptation of scientific understanding for practical purposes. Science is the understanding of nature, and astronomy is that understanding on the grandest scale. Astronomy is the science by which the universe, through its intelligent lumps of matter, tries to understand its own existence.

As the primary intelligent species on this planet, we are the custodians of a priceless gift—a planet filled with living things. This is especially true if life is rare in the universe. In fact, if Earth is the only inhabited planet, our responsibility is overwhelming. We are the only creatures who can take action to preserve the existence of life on Earth; ironically, our own actions are the most serious hazards.

The future of humanity is not secure. We are trapped on a tiny planet with limited resources and a population growing faster than our ability to produce food. We have already driven some creatures to extinction and now threaten others. We are changing the climate of our planet in ways we do not fully understand. Even if we reshape our civilization to preserve our world, the sun's evolution will eventually destroy Earth.

This may be a sad prospect, but a few factors are comforting. First, everything in the universe is temporary. Stars die, galaxies die; perhaps the entire universe will someday end. Our distant future is limited, and this assures us that we are a part of a much larger whole. Second, we have a few billion years to prepare, and a billion years is a very long time. Only a few million years ago, our ancestors were starting to walk upright and communicate. A billion years ago, our ancestors were microscopic organisms living in the oceans. To suppose that a billion years hence there will be beings resembling today's humans, or that humans will still be the dominant intelligence on Earth, or that humans will even exist, are ultimately conceits.

Our responsibility is not to save our race for all eternity but to behave as dependable custodians of our planet, preserving it, admiring it, and trying to understand it. That calls for drastic changes in our behavior toward other living things and a revolution in our attitude toward our planet's resources. Whether we can change our ways is debatable—humanity is far from perfect in its understanding, abilities, or intentions. However, you must not imagine that we, and our civilization, are less than precious. We have the gift of intelligence, and that is the finest thing this planet has ever produced.

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

—T. S. Eliot, "Little Gidding"

Excerpt from "Little Gidding" in *Four Quartets*, copyright 1942 by T. S. Eliot and renewed 1970 by Esme Valerie Eliot, reprinted by permission of Harcourt, Inc. and Faber & Faber, Ltd.

Appendix A

Units and Astronomical Data

Introduction

THE METRIC SYSTEM IS USED WORLDWIDE as the system of units, not only in science but also in engineering, business, sports, and daily life. Developed in 18th-century France, the metric system has gained acceptance in almost every country in the world because it simplifies computations.

A system of units is based on the three fundamental units for length, mass, and time. Other quantities, such as density and force, are derived from these fundamental units. In the English (or British) system of units (commonly used only in the United States, Tonga, and Southern Yemen, but, ironically, not in Great Britain) the fundamental unit of length is the foot, composed of 12 inches. The metric system is based on the decimal system of numbers, and the fundamental unit of length is the meter, composed of 100 centimeters.

Because the metric system is a decimal system, it is easy to express quantities in larger or smaller units as is convenient. You can give distances in centimeters, meters, kilometers, and so on. The prefixes specify the relation of the unit to the meter. Just as a cent is 1/100 of a dollar, so a centimeter is 1/100 of a meter. A kilometer is 1000 m, and a kilogram is 1000 g. The meanings of the commonly used prefixes are given in Table A-1.

The SI Units

ANY SYSTEM OF UNITS based on the decimal system would be easy to use; but, by international agreement, the preferred set of units, known as the *Système International d'Unités* (SI units) is based on the meter, kilogram, and second. These three fundamental units define the rest of the units, as given in Table A-2.

The SI unit of force is the newton (N), named after Isaac Newton. It is the force needed to accelerate a 1 kg mass by 1 m/s², or the force roughly equivalent to the weight of an apple at Earth's surface. The SI unit of energy is the joule (J), the energy produced by a force of 1 N acting through a distance of 1 m. A joule is roughly the energy in the impact of an apple falling off a table.

Exceptions

Units can help you in two ways. They make it possible to make calculations, and they can help you to conceive of certain quantities. For calculations, the metric system is far superior, and it is used for calculations throughout this book.

Americans commonly use the English system of units, so for conceptual purposes this book also expresses quantities in English

Table A-1 | Metric Prefixes

Prefix	Symbol	Factor
Mega	M	10 ⁶
Kilo	k	10 ³
Centi	c	10 ⁻²
Milli	m	10 ⁻³
Micro	μ	10 ⁻⁶
Nano	n	10 ⁻⁹

Table A-2 | SI (*Système International*) Metric Units

Quantity	SI Unit
Length	Meter (m)
Mass	Kilogram (kg)
Time	Second (s)
Force	Newton (N)
Energy	Joule (J)

units. Instead of saying the average person would weigh 133 N on the moon, it might be more helpful to some readers for that weight to be expressed as 30 lb. Consequently, this text commonly gives quantities in metric form followed by the English form in parentheses: The radius of the moon is 1738 km (1080 mi).

In SI units, density should be expressed as kilograms per cubic meter, but no human hand can enclose a cubic meter, so that unit does not help you grasp the significance of a given density. This book refers to density in grams per cubic centimeter. A gram is roughly the mass of a paperclip, and a cubic centimeter is the size of a small sugar cube, so you can easily conceive of a density of 1 g/cm³, roughly the density of water. This is not a bothersome departure from SI units because you will not have to make complex calculations using density.

Conversions

TO CONVERT FROM ONE METRIC UNIT to another (from meters to kilometers, for example), you have only to look at the prefix. However, converting from metric to English or English to metric is more complicated. The conversion factors are given in Table A-3.

■ **Table A-3 | Conversion Factors Between British and Metric Units**

1 inch = 2.54 centimeters	1 meter = 39.36 inches = 3.28 feet
1 foot = 0.3048 meter	1 kilometer = 0.6214 mile
1 mile = 1.609 kilometers	1 kilogram = 0.0685 slug
1 slug = 14.59 kilograms	1 Newton = 0.2248 pound
1 pound = 4.448 Newtons	1 Joule = 0.7376 foot-pound
1 foot-pound = 1.356 Joules	1 Joule/s = 0.001341 horsepower
1 horsepower = 745.7 Joules/s	1 Joule/s = 1 Watt
1 centimeter = 0.394 inch	

Example: The radius of the moon is 1738 km. What is this in miles? Table A-3 indicates that 1.000 mile equals 1.609 km, so

$$1738 \text{ km} \times \frac{(1.000 \text{ mi})}{(1.609 \text{ km})} = 1080 \text{ mi}$$

Temperature Scales

IN ASTRONOMY, as in most other sciences, temperatures are expressed on the Kelvin scale, although the centigrade (or Celsius) scale is also used. The Fahrenheit scale commonly used in the United States is not used in scientific work.

Temperatures on the Kelvin scale are measured from absolute zero, the temperature of an object that contains no extractable heat. In practice, no object can be as cold as absolute zero, although laboratory apparatuses have reached temperatures lower than 10^{-6} K. The Kelvin scale is named after the Scottish mathematical physicist William Thomson, Lord Kelvin (1824–1907).

The centigrade scale refers temperatures to the freezing point of water (0°C) and to the boiling point of water (100°C). One degree centigrade is $\frac{1}{100}$ of the temperature difference between the freezing and boiling points of water, thus the prefix *centi*. The centigrade scale is also called the Celsius scale after its inventor, the Swedish astronomer Anders Celsius (1701–1744).

The Fahrenheit scale fixes the freezing point of water at 32°F and the boiling point at 212°F . Named after the German physicist Gabriel Daniel Fahrenheit (1686–1736), who made the first successful mercury thermometer in 1720, the Fahrenheit scale is used routinely only in the United States.

It is easy to convert temperatures from one scale to another using the information given in ■Table A-4.

Powers of 10 Notation

POWERS OF 10 make writing very large numbers much simpler. For example, the nearest star is about 43,000,000,000,000 km from the sun. Writing this number as 4.3×10^{13} km is much easier.

■ **Table A-4 Temperature Scales and Conversion Formulas**

	Kelvin (K)	Centigrade ($^{\circ}\text{C}$)	Fahrenheit ($^{\circ}\text{F}$)
Absolute zero	0 K	-273°C	-459°F
Freezing point of water	273 K	0°C	32°F
Boiling point of water	373 K	100°C	212°F

Conversions:

$$\text{K} = ^{\circ}\text{C} + 273$$

$$^{\circ}\text{C} = \left(\frac{5}{9}\right)(^{\circ}\text{F} - 32)$$

$$^{\circ}\text{F} = \left(\frac{9}{5}\right)(^{\circ}\text{C}) + 32$$

Very small numbers can also be written with powers of 10. For example, the wavelength of visible light is about 0.0000005 m. In powers of 10 this becomes 5×10^{-7} m.

The powers of 10 used in this notation appear below. The exponent tells you how to move the decimal point. If the exponent is positive, move the decimal point to the right. If the exponent is negative, move the decimal point to the left. For example, 2.0000×10^3 equals 2000, and 2×10^{-3} equals 0.002.

$$10^5 = 100,000$$

$$10^4 = 10,000$$

$$10^3 = 1,000$$

$$10^2 = 100$$

$$10^1 = 10$$

$$10^0 = 1$$

$$10^{-1} = 0.1$$

$$10^{-2} = 0.01$$

$$10^{-3} = 0.001$$

$$10^{-4} = 0.0001$$

If you use scientific notation in calculations, be sure you correctly enter the numbers into your calculator. Not all calculators accept scientific notation, but those that can have a key labeled EXP, EEX, or perhaps EE that allows you to enter the exponent of ten. To enter a number such as 3×10^8 , press the keys 3 EXP 8. To enter a number with a negative exponent, you must use the change-sign key, usually labeled +/- or CHS. To enter the number 5.2×10^{-3} , press the keys 5.2 EXP +/- 3. Try a few examples.

To read a number in scientific notation from a calculator you must read the exponent separately. The number 3.1×10^{25} may appear in a calculator display as 3.1 25 or on some calculators as 3.1 10^{25} . Examine your calculator to determine how such numbers are displayed.

Astronomy Units and Constants

ASTRONOMY, AND SCIENCE IN GENERAL, is a way of learning about nature and understanding the universe. To test hypotheses about how nature works, scientists use observations of nature. The tables that follow contain some of the basic observations that support science's best understanding of the astronomical universe. Of course, these data are expressed in the form of numbers, not because science reduces all understanding to mere numbers but because the struggle to understand nature is so demanding that science must use every valid means available. Quantitative thinking—reasoning mathematically—is one of the most powerful techniques ever invented by the human brain. Thus, these tables are not nature reduced to mere numbers but numbers supporting humanity's growing understanding of the natural world around us.

■ **Table A-5** | **Astronomical Constants**

Velocity of light (c)	= 3.00×10^8 m/s
Gravitational constant (G)	= 6.67×10^{-11} m ³ /s ² kg
Mass of H atom	= 1.67×10^{-27} kg
Mass of Earth (M_{\oplus})	= 5.98×10^{24} kg
Earth equatorial radius (R_{\oplus})	= 6.38×10^3 km
Mass of sun (M_{\odot})	= 1.99×10^{30} kg
Radius of sun (R_{\odot})	= 6.96×10^8 m
Solar luminosity (L_{\odot})	= 3.83×10^{26} J/s
Mass of moon	= 7.35×10^{22} kg
Radius of moon	= 1.74×10^3 km

■ **Table A-6** | **Units Used in Astronomy**

1 Angstrom (Å)	= 10^{-8} cm = 10^{-10} m = 10 nm
1 astronomical unit (AU)	= 1.50×10^{11} m = 93.0×10^6 mi
1 light-year (ly)	= 6.32×10^4 AU = 9.46×10^{15} m = 5.88×10^{12} mi
1 parsec (pc)	= 2.06×10^5 AU = 3.09×10^{16} m = 3.26 ly
1 kiloparsec (kpc)	= 1000 pc
1 megaparsec (Mpc)	= 1,000,000 pc

■ **Table A-7** | **Properties of Main-Sequence Stars**

Spectral Type	Absolute Visual Magnitude (M_v)	Luminosity*	Temp. (K)	λ_{\max} (nm)	Mass*	Radius*	Average Density (g/cm ³)
O5	-5.8	501,000	40,000	72.4	40	17.8	0.01
B0	-4.1	20,000	28,000	100	18	7.4	0.1
B5	-1.1	790	15,000	190	6.4	3.8	0.2
A0	+0.7	79	9900	290	3.2	2.5	0.3
A5	+2.0	20	8500	340	2.1	1.7	0.6
F0	+2.6	6.3	7400	390	1.7	1.4	1.0
F5	+3.4	2.5	6600	440	1.3	1.2	1.1
G0	+4.4	1.3	6000	480	1.1	1.0	1.4
G5	+5.1	0.8	5500	520	0.9	0.9	1.6
K0	+5.9	0.4	4900	590	0.8	0.8	1.8
K5	+7.3	0.2	4100	700	0.7	0.7	2.4
M0	+9.0	0.1	3500	830	0.5	0.6	2.5
M5	+11.8	0.01	2800	1000	0.2	0.3	10.0
M8	+16	0.001	2400	1200	0.1	0.1	63

*Luminosity, mass, and radius are given in terms of the sun's luminosity, mass, and radius.

■ **Table A-8** | **The 15 Brightest Stars**

Star	Name	Apparent Visual Magnitude (m_v)	Spectral Type	Absolute Visual Magnitude (M_v)	Distance (ly)
α CMa A	Sirius	-1.47	A1	1.4	8.7
α Car	Canopus	-0.72	F0	-3.1	98
α Cen	Rigil Kentaurus	-0.01	G2	4.4	4.3
α Boo	Arcturus	-0.06	K2	-0.3	36
α Lyr	Vega	0.04	A0	0.5	26.5
α Aur	Capella	0.05	G8	-0.6	45
β Ori A	Rigel	0.14	B8	-7.1	900
α CMi A	Procyon	0.37	F5	2.7	11.3
α Ori	Betelgeuse	0.41	M2	-5.6	520
α Eri	Achernar	0.51	B3	-2.3	118
β Cen AB	Hadar	0.63	B1	-5.2	490
α Aql	Altair	0.77	A7	2.2	16.5
α Tau A	Aldebaran	0.86	K5	-0.7	68
α Cru	Acrux	0.90	B2	3.5	260
α Vir	Spica	0.91	B1	-3.3	220

■ **Table A-9** | **The 15 Nearest Stars**

Name	Absolute Magnitude (M_v)	Distance (ly)	Spectral Type	Apparent Visual Magnitude (m_v)
Sun	4.83		G2	-26.8
Proxima Cen	15.45	4.28	M5	11.05
α Cen A	4.38	4.3	G2	0.1
α Cen B	5.76	4.3	K5	1.5
Barnard's Star	13.21	5.9	M5	9.5
Wolf 359	16.80	7.6	M6	13.5
Lalande 21185	10.42	8.1	M2	7.5
Sirius A	1.41	8.6	A1	-1.5
Sirius B	11.54	8.6	white dwarf	7.2
Luyten 726-8A	15.27	8.9	M5	12.5
Luyten 726-8B (UV Cet)	15.8	8.9	M6	13.0
Ross 154	13.3	9.4	M5	10.6
Ross 248	14.8	10.3	M6	12.2
ϵ Eri	6.13	10.7	K2	3.7
Luyten 789-6	14.6	10.8	M7	12.2

■ **Table A-10** | **Properties of the Planets**

Physical Properties (Earth = \oplus)

Planet	Equatorial Radius		Mass ($\oplus = 1$)	Average Density (g/cm^3)	Surface Gravity ($\oplus = 1$)	Escape Velocity (km/s)	Sidereal Period of Rotation	Inclination of Equator to Orbit
	(km)	($\oplus = 1$)						
Mercury	2439	0.38	0.056	5.44	0.38	4.3	58.65d	0°
Venus	6052	0.95	0.815	5.24	0.90	10.3	243.02d	177°
Earth	6378	1.00	1.000	5.50	1.00	11.2	23.93h	23° .5
Mars	3396	0.53	0.108	3.94	0.38	5.0	24.62h	25° .3
Jupiter	71,494	11.20	317.8	1.34	2.54	61	9.92h	3° .1
Saturn	60,330	9.42	95.2	0.69	1.16	35.6	10.23h	26° .4
Uranus	25,559	4.01	14.5	1.19	0.92	22	17.23h	97° .9
Neptune	24,750	3.93	17.2	1.66	1.19	25	16.05h	28° .8

Orbital Properties

Planet	Semimajor Axis (a)		Orbital Period (P)		Average Orbital Velocity (km/s)	Orbital Eccentricity	Inclination to Ecliptic
	(AU)	(10^6 km)	(y)	(days)			
Mercury	0.39	57.9	0.24	87.97	47.89	0.206	7° .0
Venus	0.72	108.2	0.62	224.68	35.03	0.007	3° .4
Earth	1.00	149.6	1.00	365.26	29.79	0.017	0° *
Mars	1.52	227.9	1.88	686.95	24.13	0.093	1° .9
Jupiter	5.20	778.3	11.87	4334.3	13.06	0.048	1° .3
Saturn	9.54	1427.0	29.46	10,760	9.64	0.056	2° .5
Uranus	19.18	2869.0	84.01	30,685	6.81	0.046	0° .8
Neptune	30.06	4497.1	164.79	60,189	5.43	0.010	1° .8

* By definition.

■ **Table A-11** | **Principal Satellites of the Solar System**

Planet	Satellite	Radius (km)	Distance from Planet (10 ³ km)	Orbital Period (days)	Orbital Eccentricity	Orbital Inclination
Earth	Moon	1738	384.4	27.32	0.055	5°.1
Mars	Phobos	14 × 12 × 10	9.4	0.32	0.018	1°.0
	Deimos	8 × 6 × 5	23.5	1.26	0.002	2°.8
Jupiter	Amalthea	135 × 100 × 78	182	0.50	0.003	0°.4
	Io	1820	422	1.77	0.000	0°.3
	Europa	1565	671	3.55	0.000	0°.5
	Ganymede	2640	1071	7.16	0.002	0°.2
	Callisto	2420	1884	16.69	0.008	0°.2
	Himalia	~ 85	11,470	250.6	0.158	27°.6
	Saturn	Janus	110 × 80 × 100	151.5	0.70	0.007
Saturn	Mimas	196	185.5	0.94	0.020	1°.5
	Enceladus	250	238.0	1.37	0.004	0°.0
	Tethys	530	294.7	1.89	0.000	1°.1
	Dione	560	377	2.74	0.002	0°.0
	Rhea	765	527	4.52	0.001	0°.4
	Titan	2575	1222	15.94	0.029	0°.3
	Hyperion	205 × 130 × 110	1484	21.28	0.104	~0°.5
	Iapetus	720	3562	79.33	0.028	14°.7
	Phoebe	110	12,930	550.4	0.163	150°
	Uranus	Miranda	242	129.9	1.41	0.017
Uranus	Ariel	580	190.9	2.52	0.003	0°
	Umbriel	595	266.0	4.14	0.003	0°
	Titania	805	436.3	8.71	0.002	0°
	Oberon	775	583.4	13.46	0.001	0°
Neptune	Proteus	205	117.6	1.12	~0	~0°
	Triton	1352	354.59	5.88	0.00	160°
	Nereid	170	5588.6	360.12	0.76	27.7°

■ **Table A-12** | **Meteor Showers**

Shower	Dates	Hourly Rate	Radiant of shower		Associated Comet
			R.A.	Dec.	
Quadrantids	Jan. 2–4	30	15 ^h 24 ^m	50°	
Lyrids	April 20–22	8	18 ^h 4 ^m	33°	1861 I
η Aquarids	May 2–7	10	22 ^h 24 ^m	0°	Halley?
δ Aquarids	July 26–31	15	22 ^h 36 ^m	–10°	
Perseids	Aug. 10–14	40	3 ^h 4 ^m	58°	Swift-Tuttle
Orionids	Oct. 18–23	15	6 ^h 20 ^m	15°	Halley?
Taurids	Nov. 1–7	8	3 ^h 40 ^m	17°	Encke
Leonids	Nov. 14–19	6	10 ^h 12 ^m	22°	1866 I Temp
Geminids	Dec. 10–13	50	7 ^h 28 ^m	32°	

■ **Table A-13** | **Greatest Elongations of Mercury***

Evening Sky	Morning Sky
Dec. 18, 2009	Jan. 27, 2010
Apr. 8, 2010**	May 26, 2010
Aug. 7, 2010	Sept. 19, 2010**
Dec. 1, 2010	Jan. 9, 2011
March 23, 2011**	May 7, 2011
July 20, 2011	Sept. 3, 2011**
Nov. 14, 2011	Dec. 23, 2011
March 5, 2012**	April 18, 2012
July 1, 2012	Aug. 16, 2012
Oct. 26, 2012	Dec. 4, 2012
Feb. 16, 2013	March 31, 2013
June 12, 2013	July 30, 2013
Oct. 9, 2013	Nov. 18, 2013

*Elongation is the angular distance from the sun to a planet.

**Most favorable elongations.

■ **Table A-14** | **Greatest Elongations of Venus**

Evening Sky	Morning Sky
Aug. 20, 2010	Jan. 8, 2011
March 27, 2012	Aug. 15, 2012
Nov. 1, 2013	March 22, 2014
June 6, 2015	Oct. 26, 2015
Jan. 12, 2017	June 3, 2017
Aug. 17, 2018	Jan. 6, 2019
March 24, 2020	Aug. 12, 2020

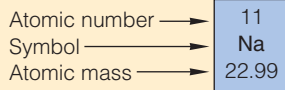
■ **Table A-15** | **The Greek Alphabet**

A , α alpha	H , η eta	N , ν nu	T , τ tau
B , β beta	Θ , θ theta	Ξ , ξ xi	Υ , υ upsilon
Γ , γ gamma	I , ι iota	O , ο omicron	Φ , φ phi
Δ , δ delta	K , κ kappa	Π , π pi	X , χ chi
E , ε epsilon	Λ , λ lambda	P , ρ rho	Ψ , ψ psi
Z , ζ zeta	M , μ mu	Σ , σ sigma	Ω , ω omega

Table A-16 | Periodic Table of the Elements

Group																		Noble Gases						
IA(1)																		(18)						
1	1 H 1.008																	2 He 4.003						
2	3 Li 6.941	4 Be 9.012																	5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31	Transition Elements										13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95						
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.7	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80						
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3						
6	55 Cs 132.9	56 Ba 137.3	57* La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)						
7	87 Fr (223)	88 Ra 226.0	89** Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 Ds (269)	111 Uuu (272)	112 Uub (277)	113 Uub (284)	114 Uuq (285)	115 Uub (288)	116 Uuh (289)								

Atomic masses are based on carbon-12. Numbers in parentheses are mass numbers of most stable or best-known isotopes of radioactive elements.



Inner Transition Elements

Lanthanide Series	6	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinide Series	7	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.0	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

The Elements and Their Symbols

Actinium	Ac	Cesium	Cs	Hafnium	Hf	Mercury	Hg	Protactinium	Pa	Tellurium	Te
Aluminum	Al	Chlorine	Cl	Hassium	Hs	Molybdenum	Mo	Radium	Ra	Terbium	Tb
Americium	Am	Chromium	Cr	Helium	He	Neodymium	Nd	Radon	Rn	Thallium	Tl
Antimony	Sb	Cobalt	Co	Holmium	Ho	Neon	Ne	Rhenium	Re	Thorium	Th
Argon	Ar	Copper	Cu	Hydrogen	H	Neptunium	Np	Rhodium	Rh	Thulium	Tm
Arsenic	As	Curium	Cm	Indium	In	Nickel	Ni	Rubidium	Rb	Tin	Sn
Astatine	At	Darmstadtium	Ds	Iodine	I	Niobium	Nb	Ruthenium	Ru	Titanium	Ti
Barium	Ba	Dubnium	Db	Iridium	Ir	Nitrogen	N	Rutherfordium	Rf	Tungsten	W
Berkelium	Bk	Dysprosium	Dy	Iron	Fe	Nobelium	No	Samarium	Sm	Uranium	U
Beryllium	Be	Einsteinium	Es	Krypton	Kr	Osmium	Os	Scandium	Sc	Vanadium	V
Bismuth	Bi	Erbium	Er	Lanthanum	La	Oxygen	O	Seaborgium	Sg	Xenon	Xe
Bohrium	Bh	Europium	Eu	Lawrencium	Lr	Palladium	Pd	Selenium	Se	Ytterbium	Yb
Boron	B	Fermium	Fm	Lead	Pb	Phosphorus	P	Silicon	Si	Yttrium	Y
Bromine	Br	Fluorine	F	Lithium	Li	Platinum	Pt	Silver	Ag	Zinc	Zn
Cadmium	Cd	Francium	Fr	Lutetium	Lu	Plutonium	Pu	Sodium	Na	Zirconium	Zr
Calcium	Ca	Gadolinium	Gd	Magnesium	Mg	Polonium	Po	Strontium	Sr		
Californium	Cf	Gallium	Ga	Manganese	Mn	Potassium	K	Sulfur	S		
Carbon	C	Germanium	Ge	Meitnerium	Mt	Praseodymium	Pr	Tantalum	Ta		
Cerium	Ce	Gold	Au	Mendelevium	Md	Promethium	Pm	Technetium	Tc		

Appendix B

Observing the Sky

OBSERVING THE SKY WITH THE NAKED EYE is as important to modern astronomy as picking up pretty pebbles is to modern geology. Nevertheless, the sky is inspiring—a natural wonder unimaginably bigger than the Grand Canyon, the Rocky Mountains, or any other site that tourists visit every year. To neglect the beauty of the sky is equivalent to geologists neglecting the beauty of the minerals they study. This supplement is meant to act as a tourist's guide to the sky. You analyzed the universe in the textbook's chapters; here you can admire it.

The brighter stars in the sky are visible even from the centers of cities with their air and light pollution. But in the countryside, only a few miles beyond the cities, the night sky is a velvety blackness strewn with thousands of glittering stars. From a wilderness location, far from the city's glare, and especially from high mountains, the night sky is spectacular.

Using Star Charts

THE CONSTELLATIONS ARE A FASCINATING CULTURAL HERITAGE of our planet, but they are sometimes a bit difficult to learn because of Earth's motion. The constellations above the horizon change with the time of night and the seasons.

Because Earth rotates eastward, the sky appears to rotate westward around Earth. A constellation visible overhead soon after sunset will appear to move westward, and in a few hours it will disappear below the horizon. Other constellations will rise in the east, so the sky changes gradually through the night.

In addition, Earth's orbital motion makes the sun appear to move eastward among the stars. Each day the sun moves about twice its own diameter, or about one degree, eastward along the ecliptic; consequently, each night at sunset, the constellations are shifted about one degree farther toward the west.

Orion, for instance, is visible in the evening sky in January; but, as the days pass, the sun moves closer to Orion. By March, Orion is difficult to see in the western sky soon after sunset. By June, the sun is so close to Orion it sets with the sun and is invisible. Not until late July is the sun far enough past Orion for the

constellation to become visible rising in the eastern sky just before dawn.

Because of the rotation and orbital motion of Earth, you need more than one star chart to map the sky. Which chart you select depends on the month and the time of night.

Two sets of charts are included for two typical locations on Earth. The Northern Hemisphere star charts show the sky as seen from a northern latitude typical for the United States and Central Europe. The Southern Hemisphere star charts are appropriate for readers in Earth's Southern Hemisphere, including Australia, southern South America, and southern Africa.

To use the charts, select the appropriate chart and hold it overhead as shown in ■ Figure B-1. If you face south, turn the chart until the words *Southern Horizon* are at the bottom of the chart. If you face other directions, turn the chart appropriately.



■ **Figure B-1**

To use the star charts in this book, select the appropriate chart for the season and time. Hold it overhead and turn it until the direction at the bottom of the chart is the same as the direction you are facing.

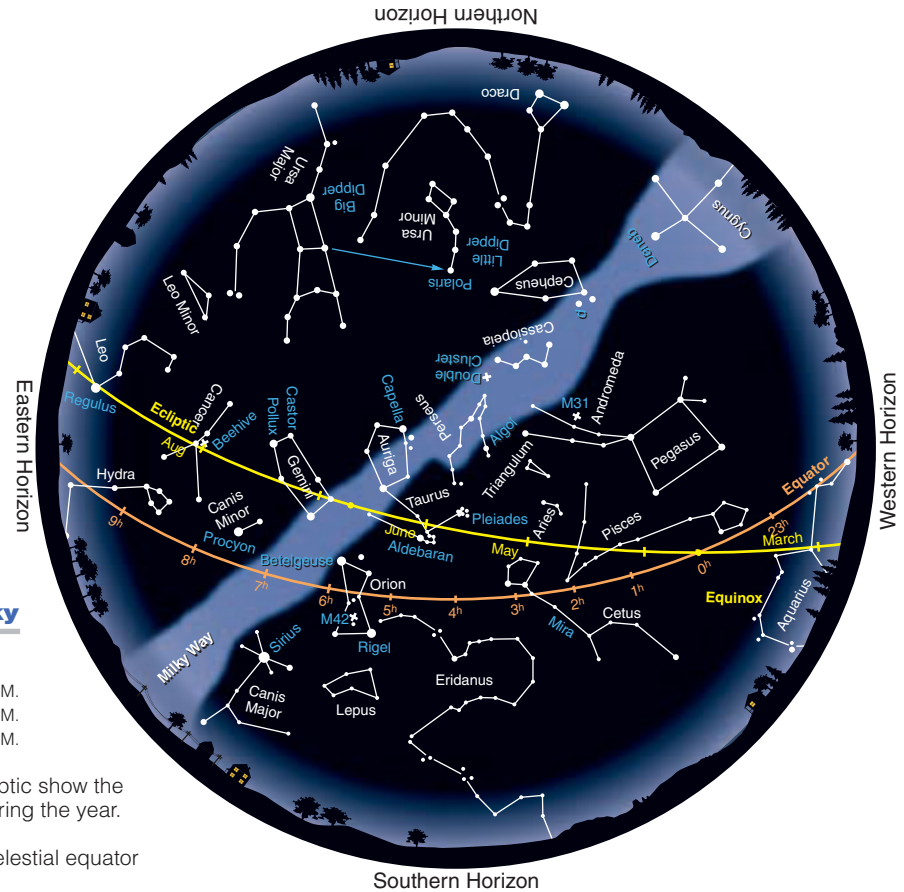
Northern Hemisphere Sky

JANUARY

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



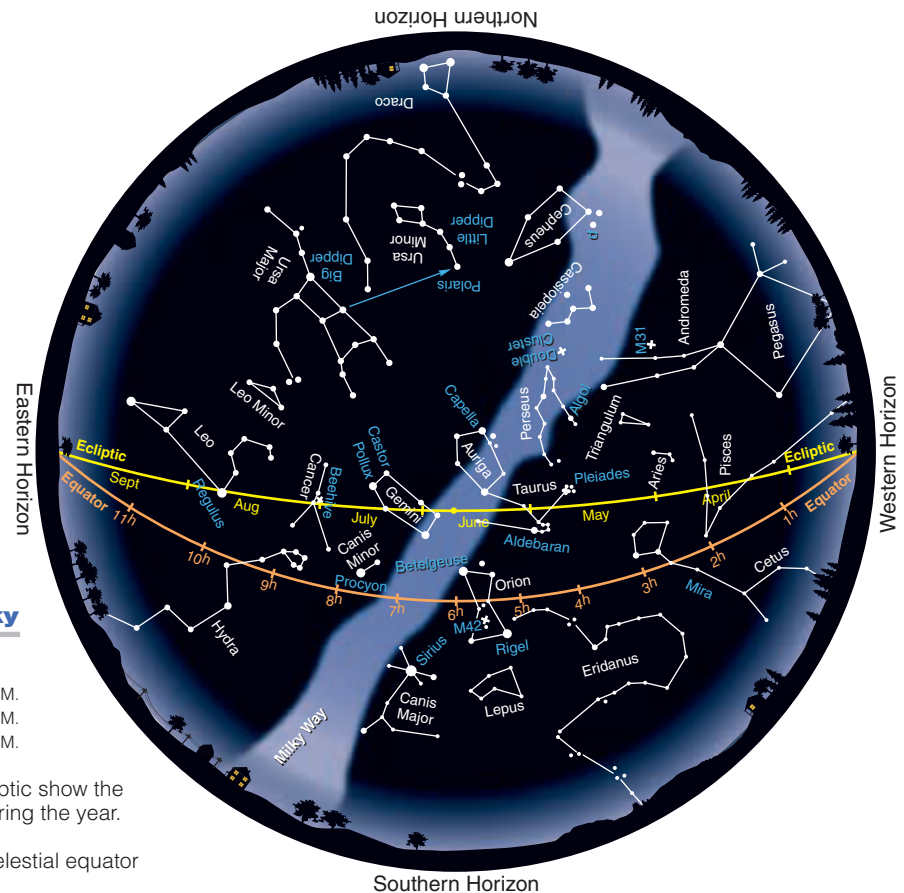
Northern Hemisphere Sky

FEBRUARY

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



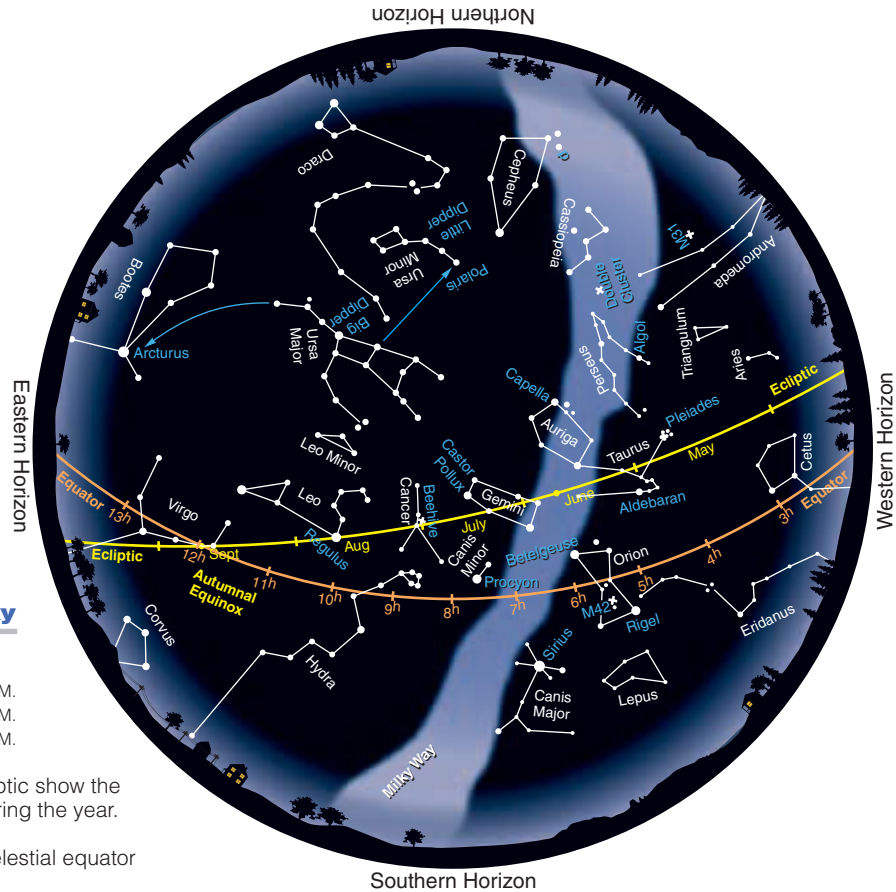
Northern Hemisphere Sky

MARCH

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



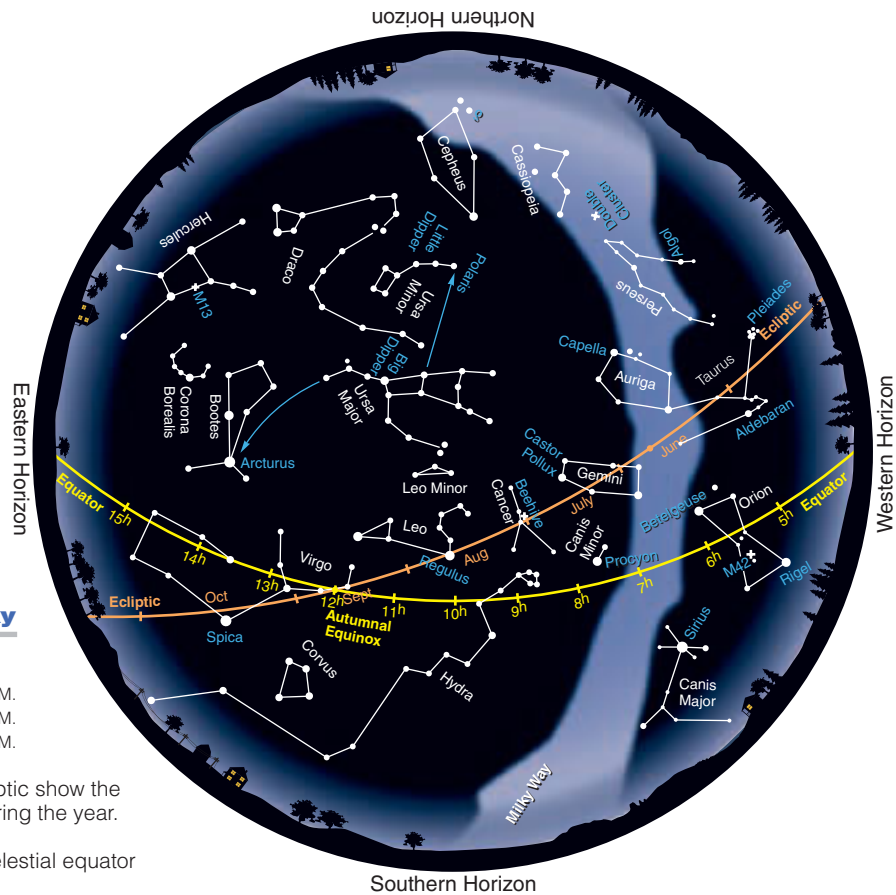
Northern Hemisphere Sky

APRIL

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



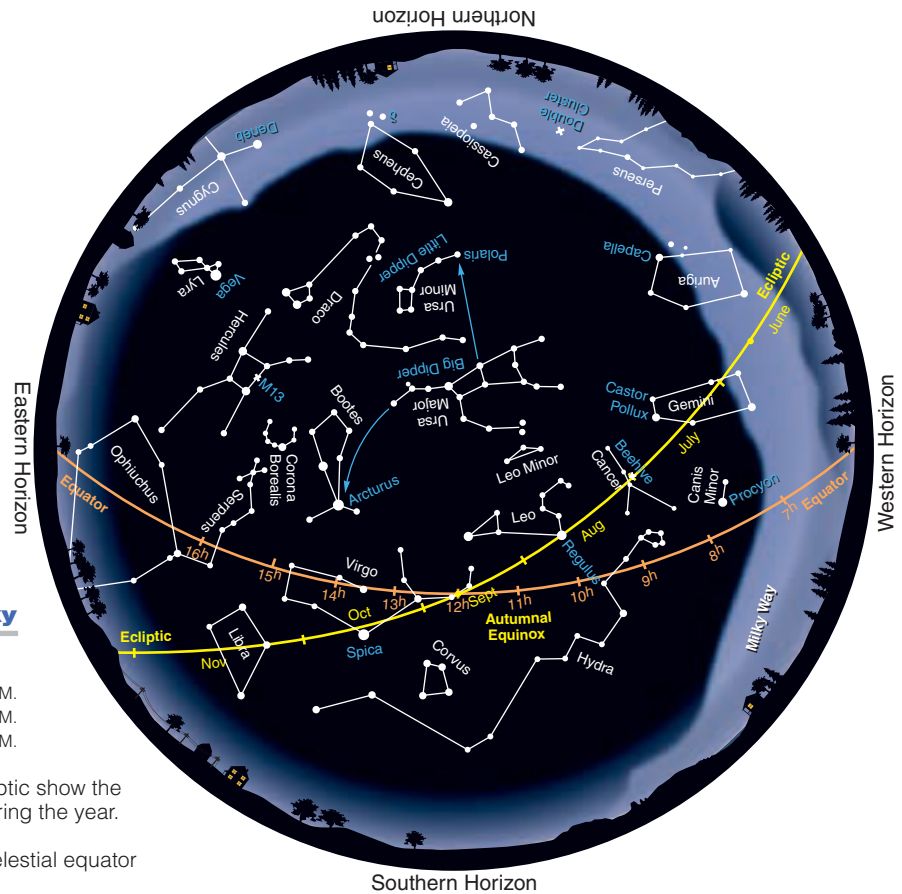
Northern Hemisphere Sky

MAY

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



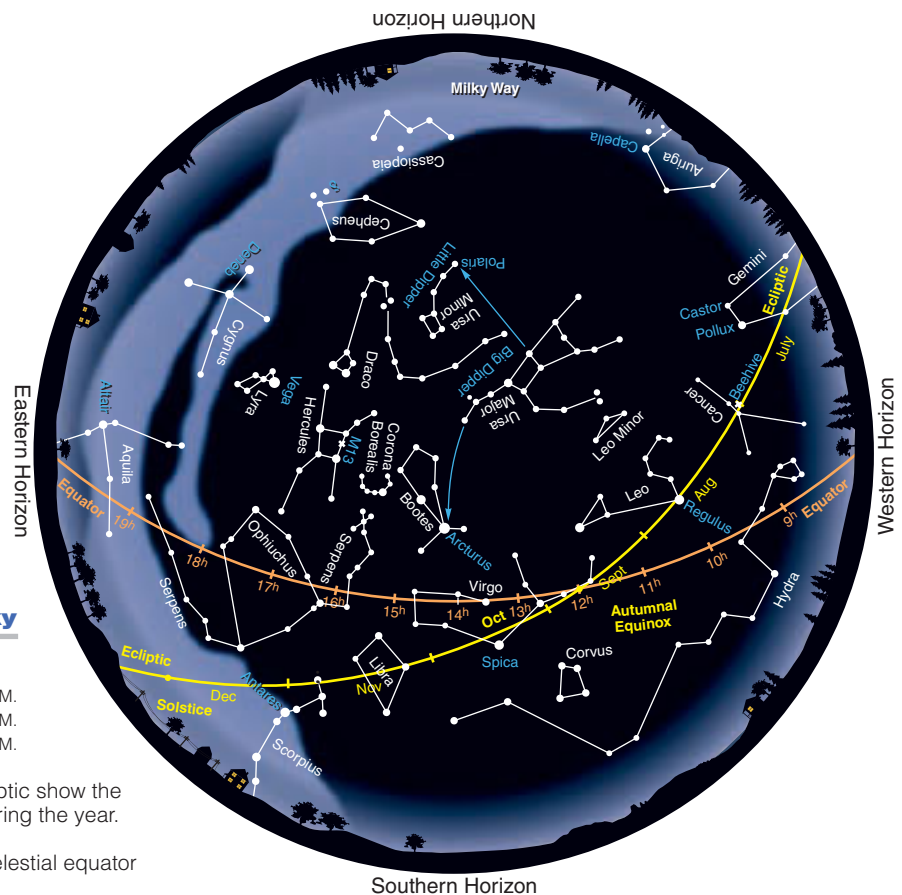
Northern Hemisphere Sky

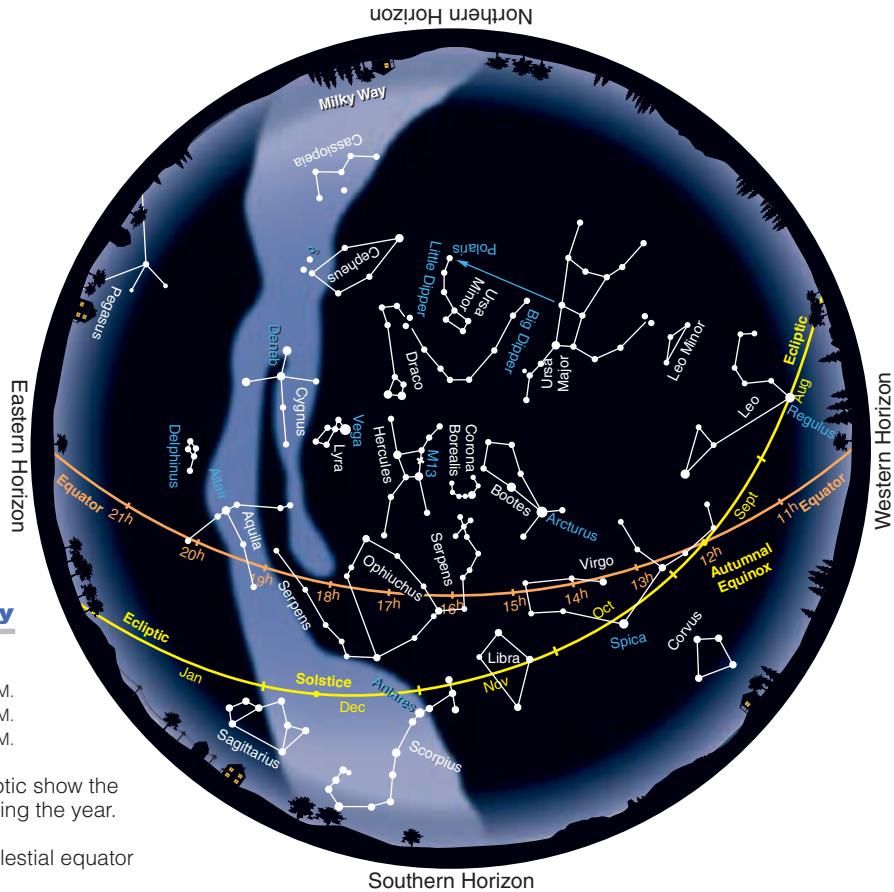
JUNE

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



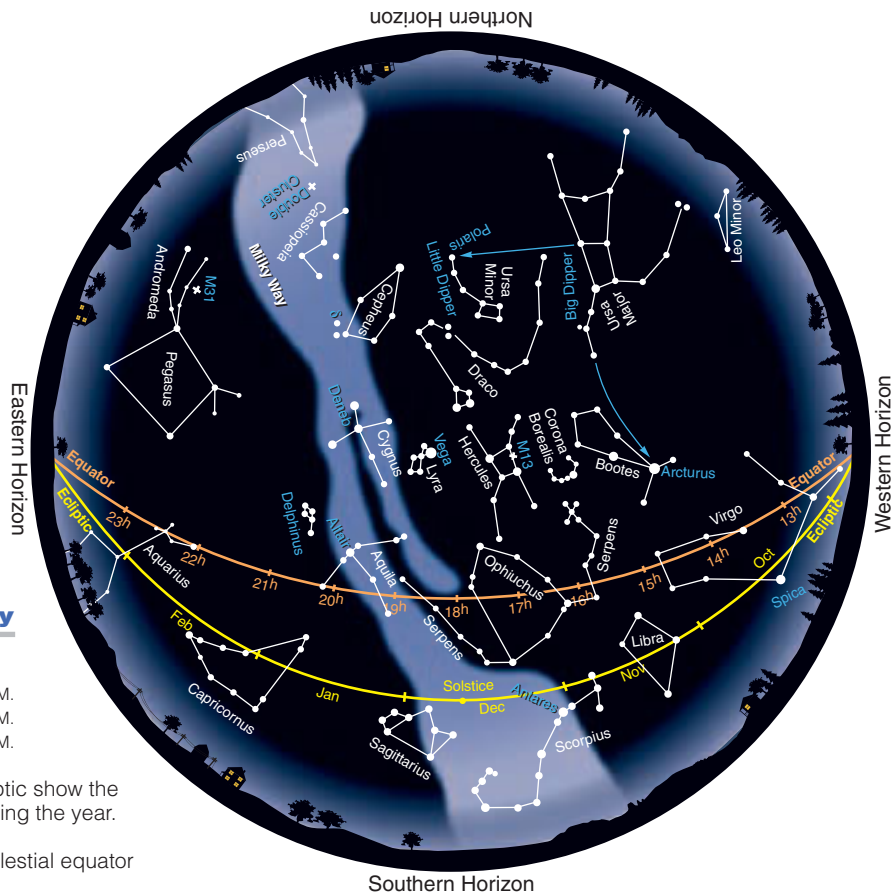


Northern Hemisphere Sky

JULY
 Early in Month 9 P.M.
 Midmonth 8 P.M.
 End of Month 7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



Northern Hemisphere Sky

AUGUST
 Early in Month 9 P.M.
 Midmonth 8 P.M.
 End of Month 7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.

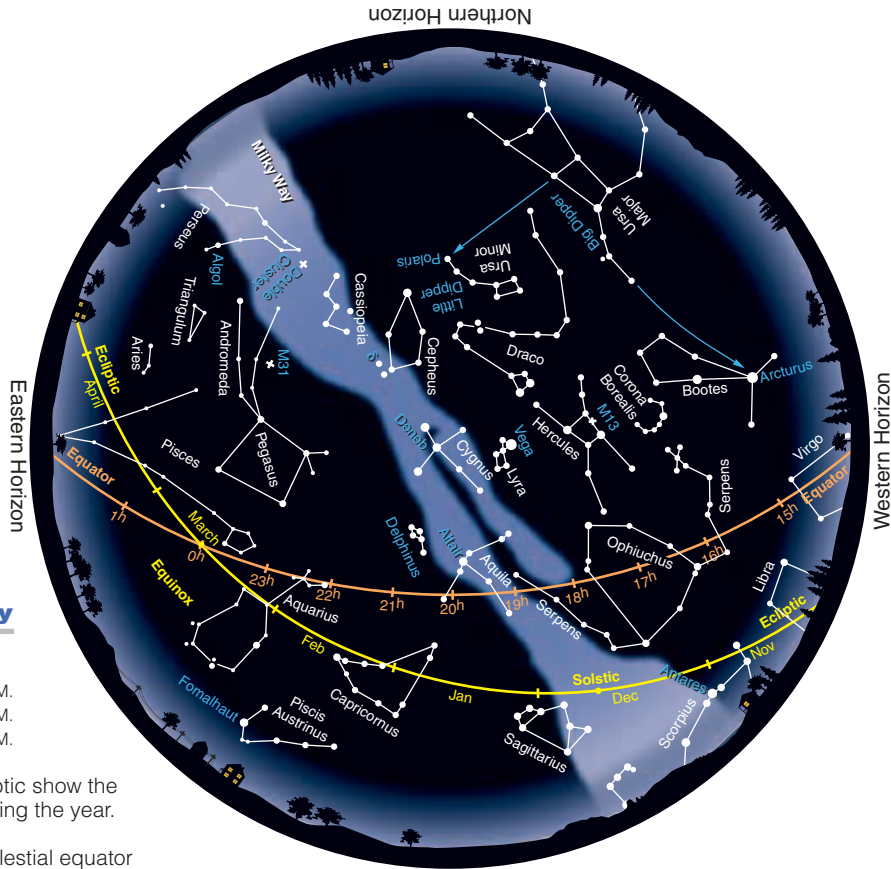
Northern Hemisphere Sky

SEPTEMBER

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



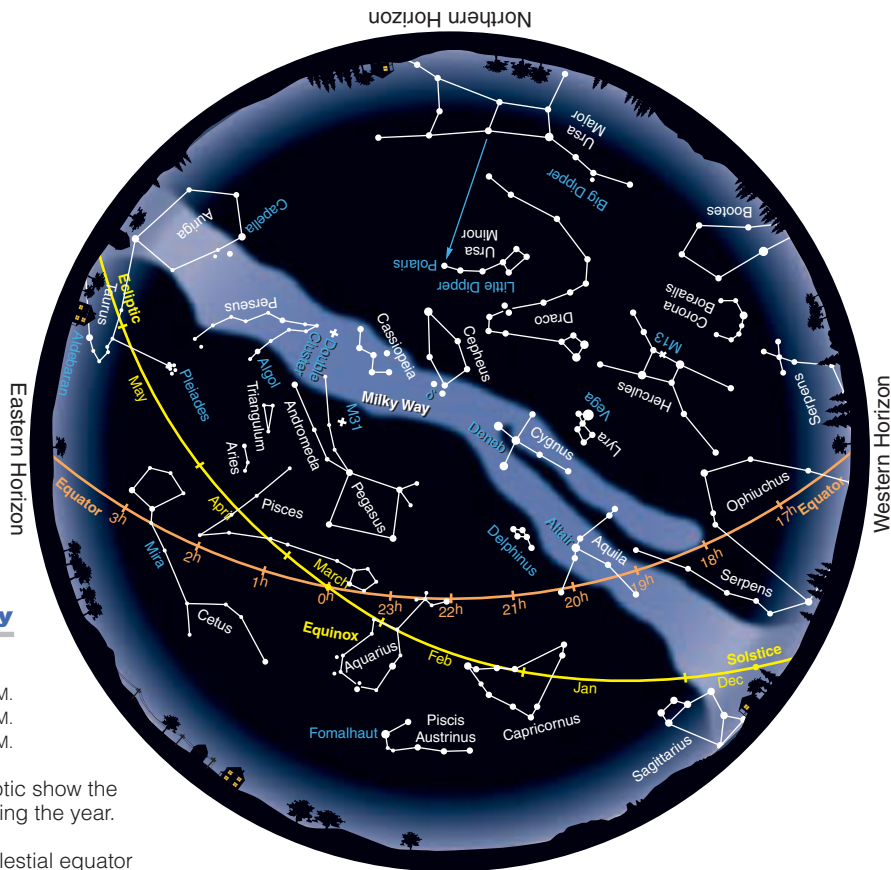
Northern Hemisphere Sky

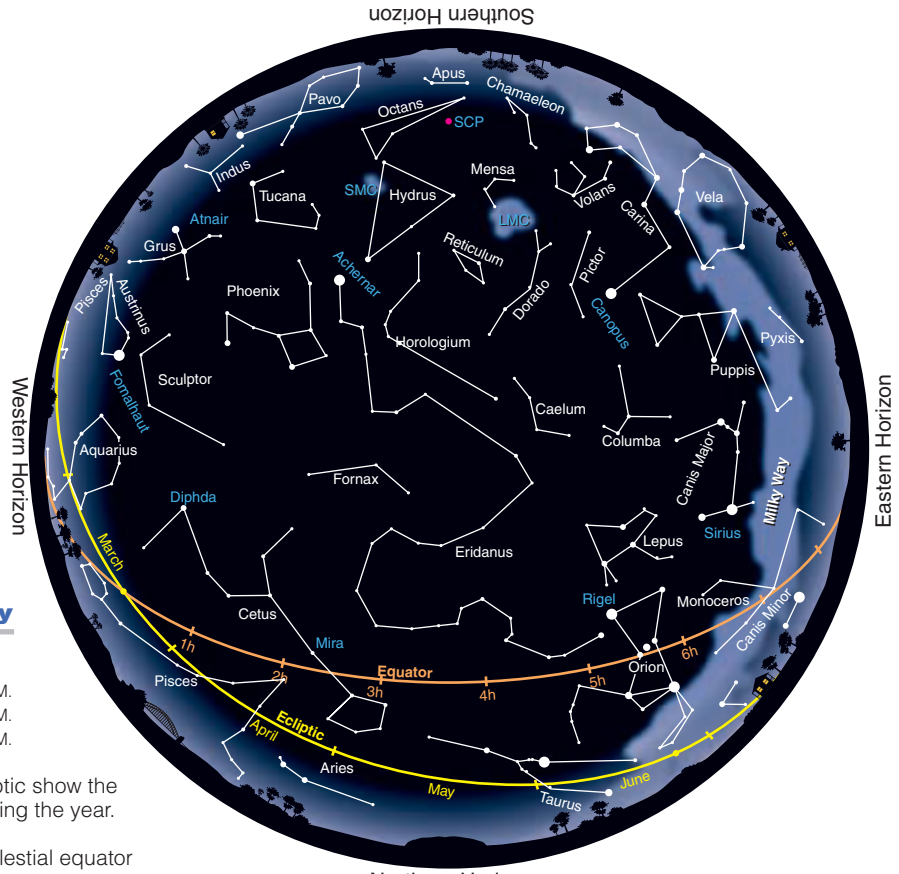
OCTOBER

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



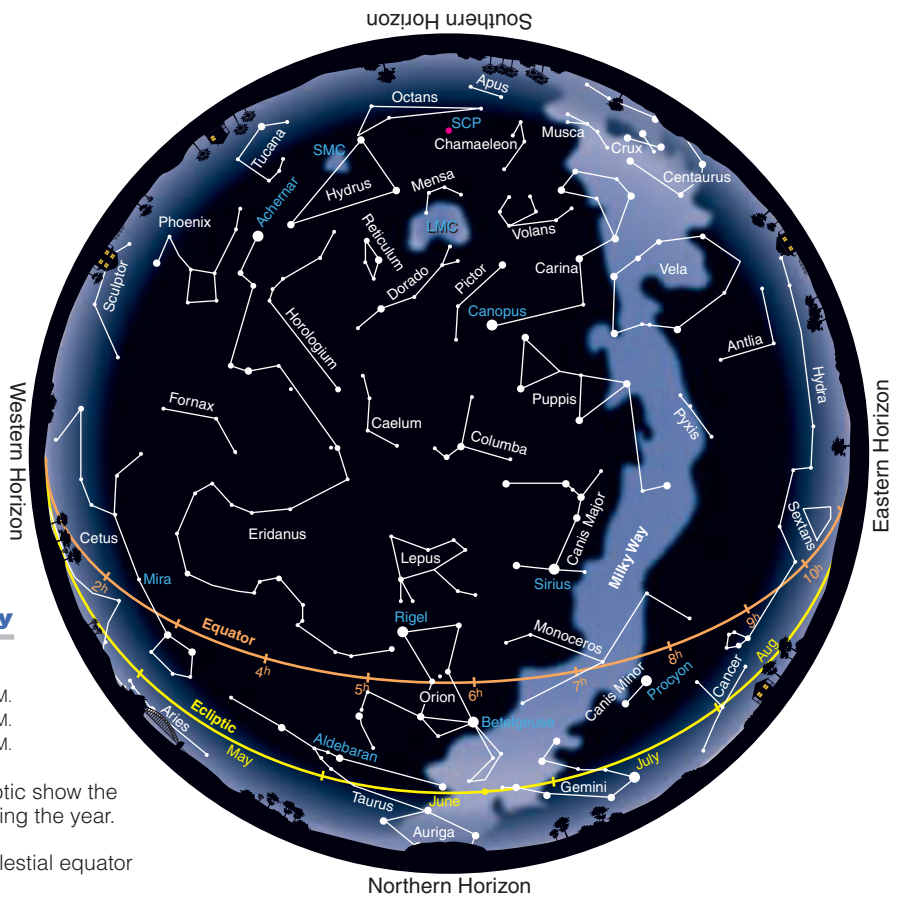


Southern Hemisphere Sky

JANUARY
 Early in Month 9 P.M.
 Midmonth 8 P.M.
 End of Month 7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.

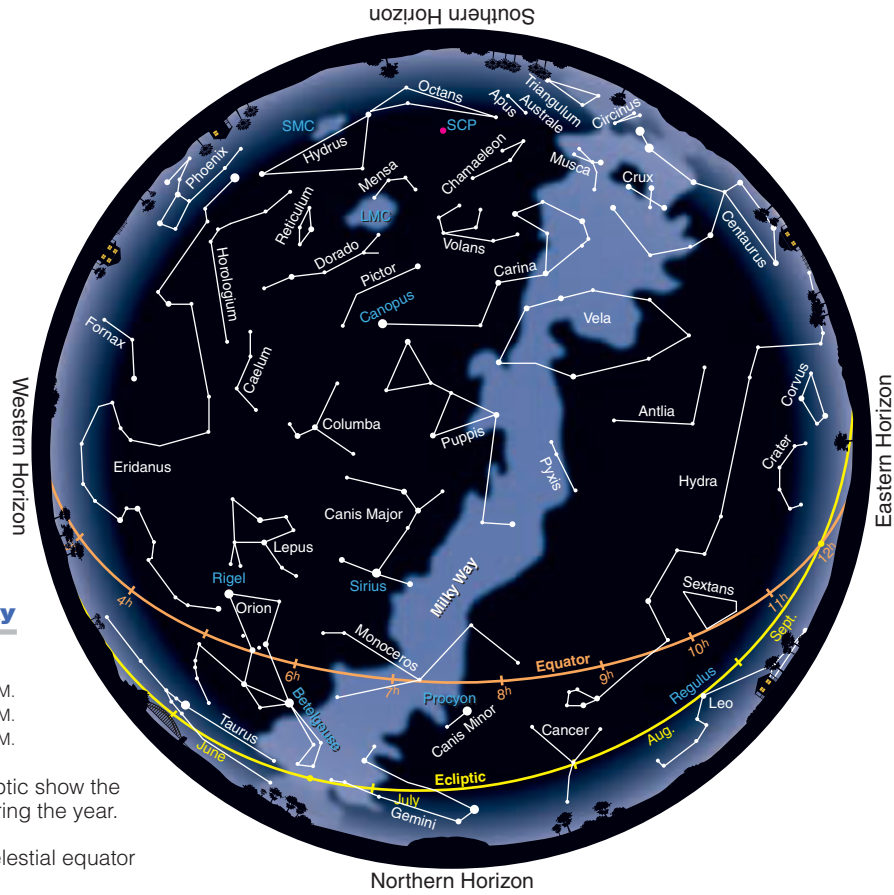


Southern Hemisphere Sky

FEBRUARY
 Early in Month 9 P.M.
 Midmonth 8 P.M.
 End of Month 7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



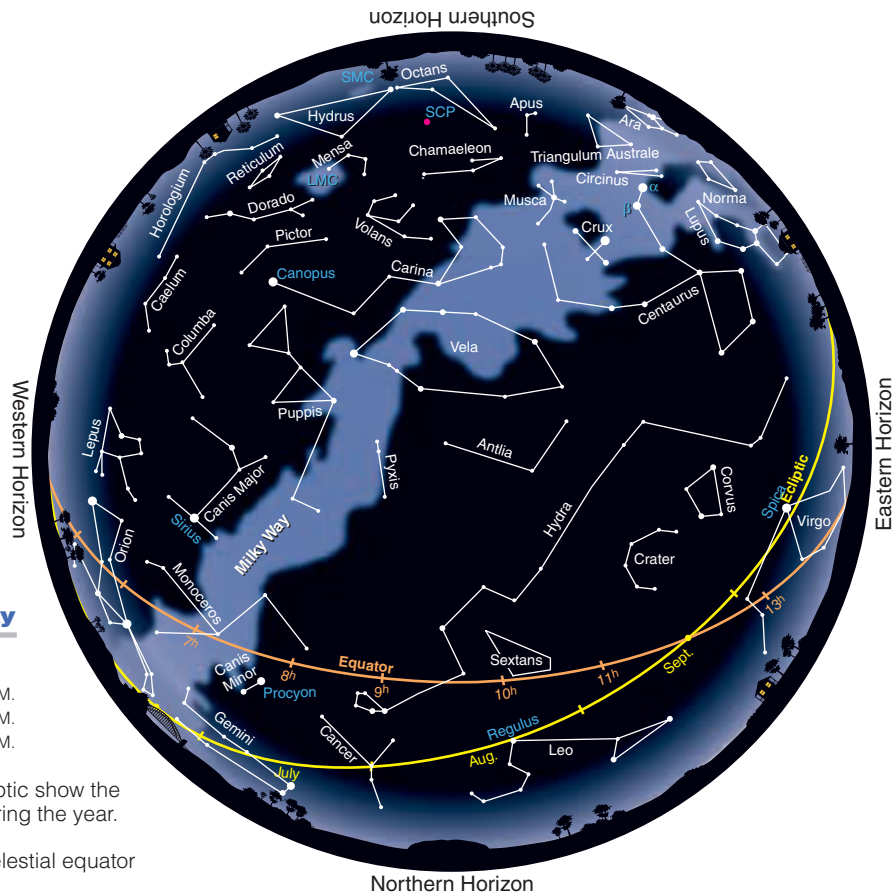
Southern Hemisphere Sky

MARCH

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



Southern Hemisphere Sky

APRIL

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.

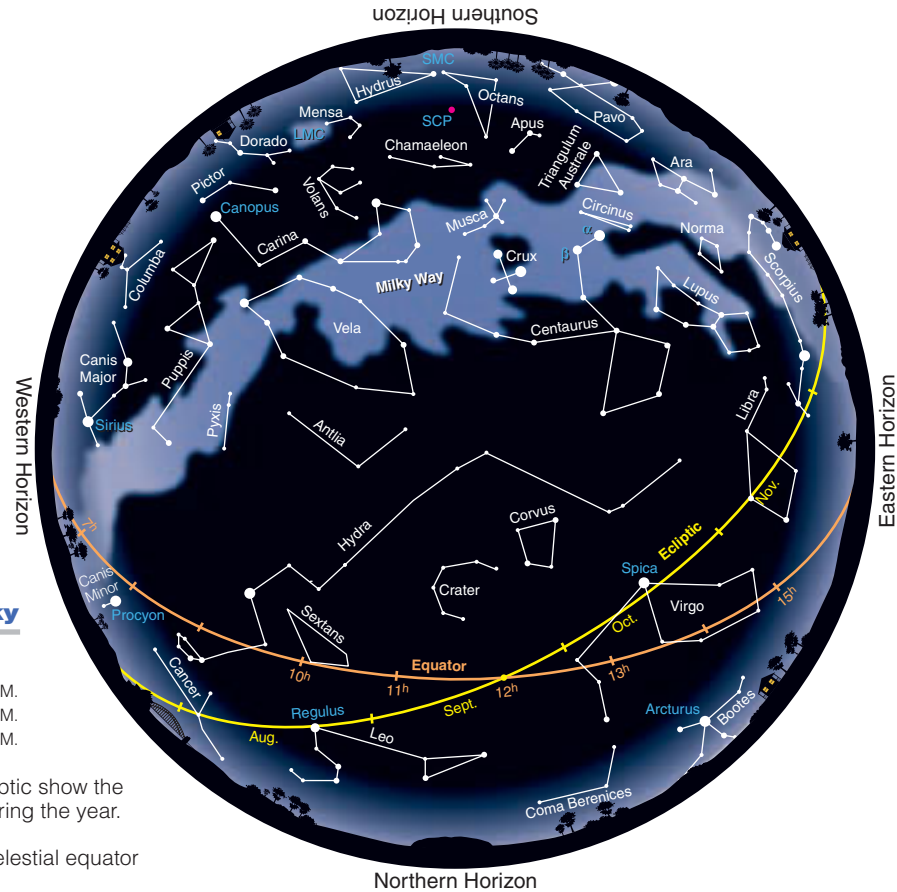
Southern Hemisphere Sky

MAY

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



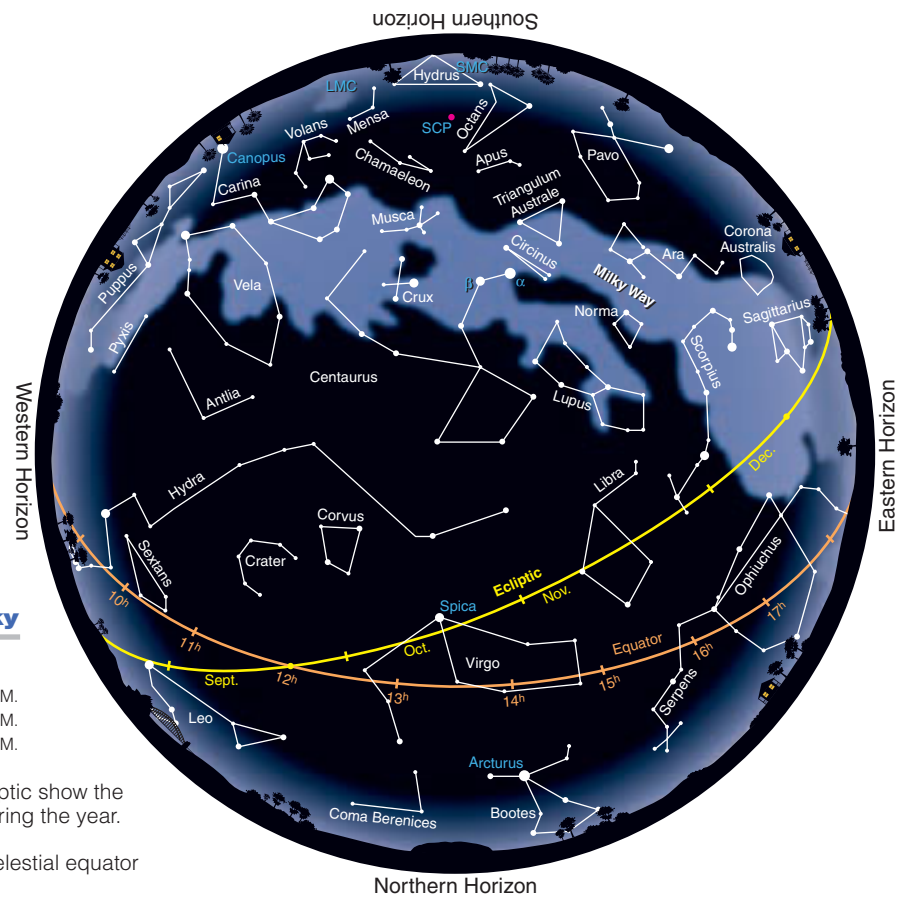
Southern Hemisphere Sky

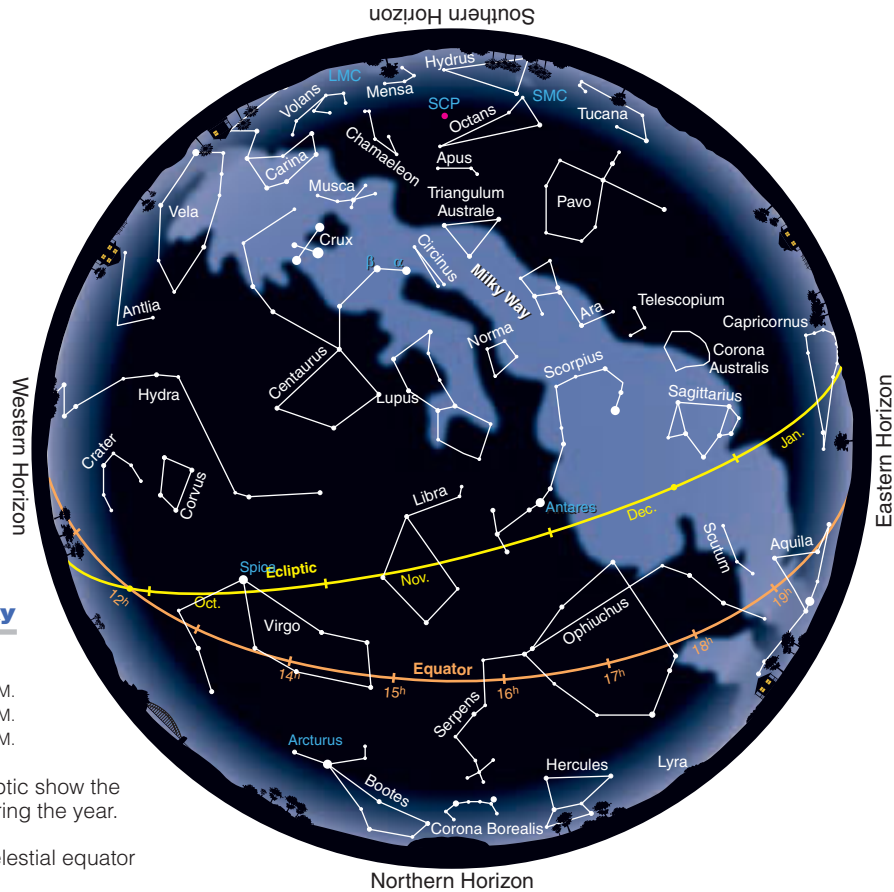
JUNE

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.







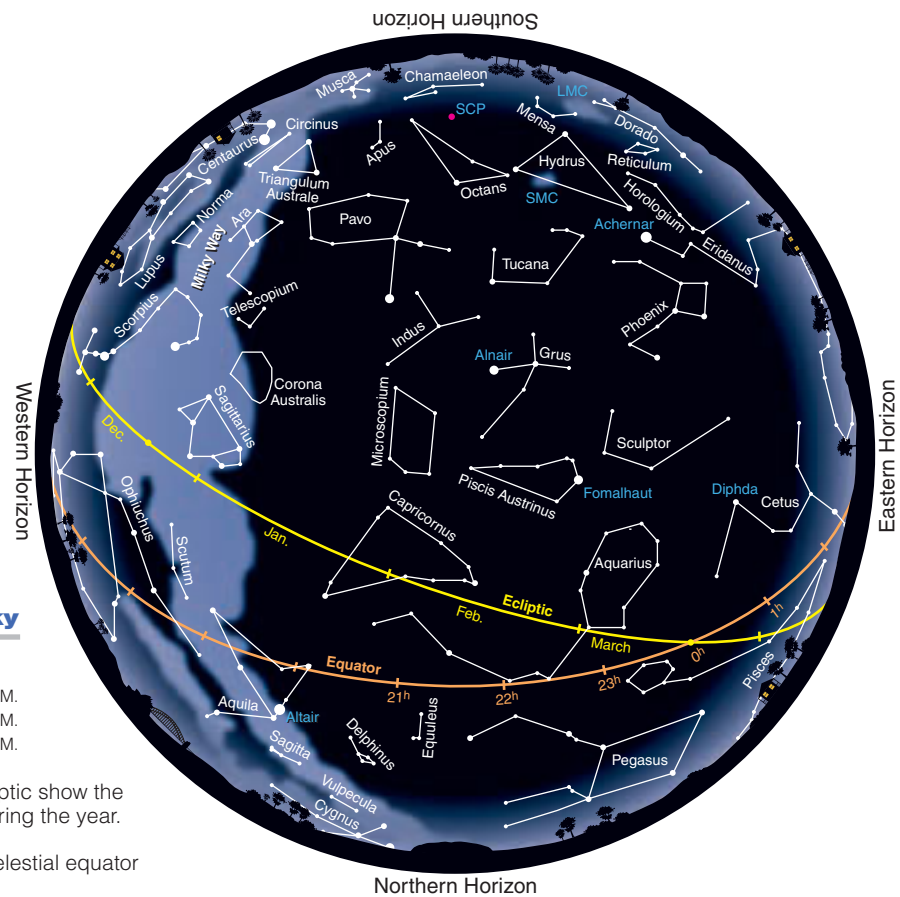
Southern Hemisphere Sky

SEPTEMBER

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



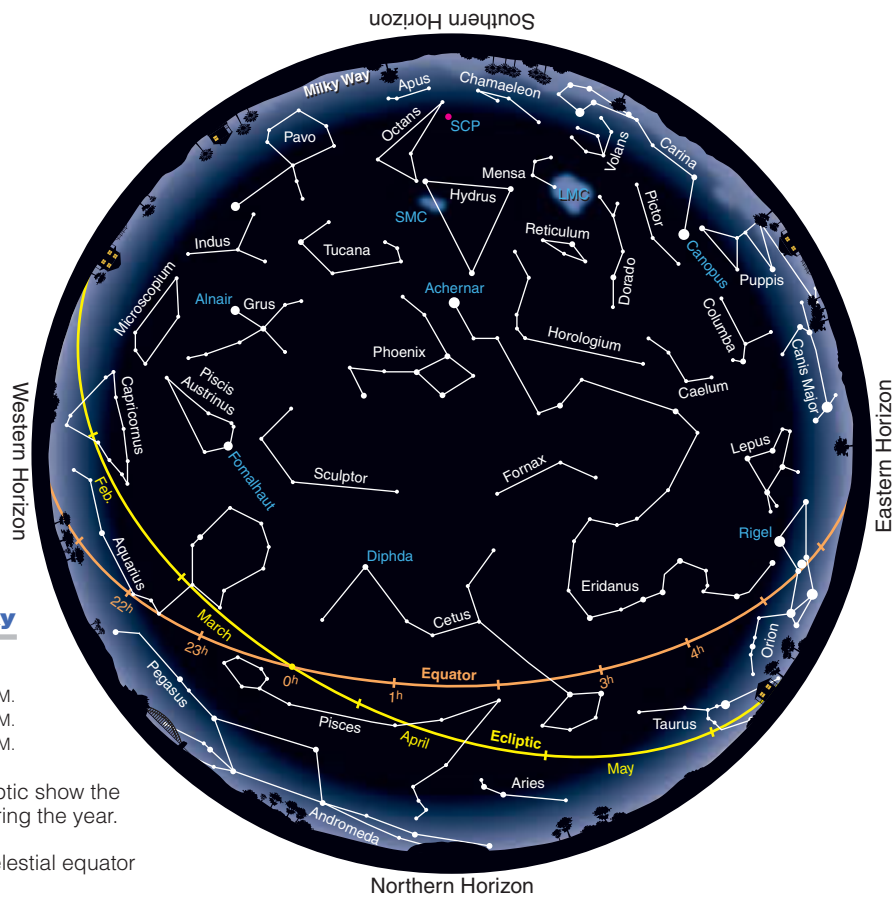
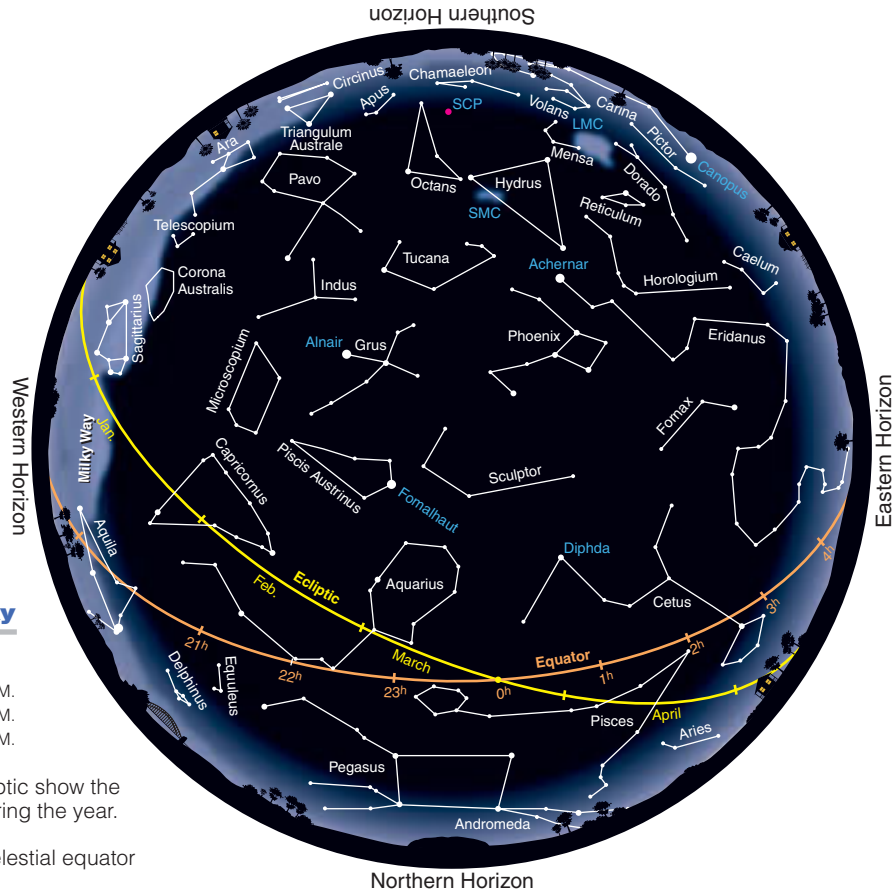
Southern Hemisphere Sky

OCTOBER

Early in Month	9 P.M.
Midmonth	8 P.M.
End of Month	7 P.M.

Months along the ecliptic show the location of the sun during the year.

Numbers along the celestial equator show right ascension.



Glossary

Numbers in parentheses refer to the page where the term is first discussed in the text.

absolute bolometric magnitude (172) The absolute magnitude you would observe if you could detect all wavelengths.

absolute visual magnitude (M_V) (171) Intrinsic brightness of a star; the apparent visual magnitude the star would have if it were 10 pc away.

absolute zero (127) The lowest possible temperature; the temperature at which the particles in a material, atoms or molecules, contain no energy of motion that can be extracted from the body.

absorption line (132) A dark line in a spectrum; produced by the absence of photons absorbed by atoms or molecules.

absorption (dark-line) spectrum (132) A spectrum that contains absorption lines.

acceleration (79) A change in a velocity; a change in either speed or direction. (See *velocity*.)

acceleration of gravity (77) A measure of the strength of gravity at a planet's surface.

accretion disk (264) The whirling disk of gas that forms around a compact object such as a white dwarf, neutron star, or black hole as matter is drawn in.

achromatic lens (102) A telescope lens composed of two lenses ground from different kinds of glass and designed to bring two selected colors to the same focus and correct for chromatic aberration.

active galactic nucleus (AGN) (356) The central energy source of an active galaxy.

active galaxy (356) A galaxy that is a source of excess radiation, usually radio waves, X-rays, gamma rays, or some combination.

active optics (111) Optical elements whose position or shape is continuously controlled by computers.

active region (155) An area on the sun where sunspots, prominences, flares, and the like occur.

adaptive optics (109) Computer-controlled telescope mirrors that can at least partially compensate for seeing.

alt-azimuth mounting (111) A telescope mounting capable of motion parallel to and perpendicular to the horizon.

amino acid (400) One of the carbon-chain molecules that are the building blocks of protein.

Angstrom (\AA) (100) A unit of distance; $1 \text{\AA} = 10^{-10}$ m; often used to measure the wavelength of light.

angular diameter (19) A measure of the size of an object in the sky; numerically equal to the angle in degrees between two lines extending from the observer's eye to opposite edges of the object.

angular distance (19) A measure of the separation between two objects in the sky; numerically equal to the angle in degrees between two lines extending from the observer's eye to the two objects.

angular momentum (83) The tendency of a rotating body to continue rotating; mathematically, the product of mass, velocity, and radius.

annular eclipse (39) A solar eclipse in which the solar photosphere appears around the edge of the moon in a bright ring, or annulus. The corona, chromosphere, and prominences cannot be seen.

antcoded (411) Message designed to be understood by a recipient about whom the sender knows little or nothing, for example an interstellar broadcast aimed at possible inhabitants of another planet.

antimatter (376) Matter composed of antiparticles, which on colliding with a matching particle of normal matter annihilate and convert the mass of both particles into energy. The antiproton is the antiparticle of the proton, and the positron is the antiparticle of the electron.

aphelion (23) The orbital point of greatest distance from the sun.

apogee (39) The orbital point of greatest distance from Earth.

apparent visual magnitude (m_v) (15) The brightness of a star as seen by human eyes on Earth.

archaea (407) A biological kingdom of microorganisms similar to, but distinct from, bacteria, with characteristics most closely resembling those inferred for the common ancestor of all present-day Earth life.

arc minute (19) An angular measure; each degree is divided into 60 arc minutes.

arc second (19) An angular measure; each arc minute is divided into 60 arc seconds.

archaeoastronomy (50) The study of the astronomy of ancient cultures.

association (224) Group of widely scattered stars (10 to 1000) moving together through space; not gravitationally bound into a cluster.

asterism (13) A named group of stars not identified as a constellation, e.g., the Big Dipper.

astrobiology (398) The field of study involving searches for life on other worlds and investigation of possible habitats for such life. Also known as "exobiology."

astronomical unit (AU) (4) Average distance from Earth to the sun; 1.5×10^8 km, or 93×10^6 miles.

atmospheric window (101) Wavelength region in which Earth's atmosphere is transparent—at visual, infrared, and radio wavelengths.

aurora (163) The glowing light display that results when a planet's magnetic field guides charged particles toward the north and south magnetic poles, where they strike the upper atmosphere and excite atoms to emit photons.

autumnal equinox (22) The point on the celestial sphere where the sun crosses the celestial equator going southward. Also, the time when the sun reaches this point and autumn begins in the Northern Hemisphere—about September 22.

Babcock model (158) A model of the sun's magnetic cycle in which the differential rotation of the sun winds up and tangles the solar magnetic field in a 22-year cycle. This is thought to be responsible for the 11-year sunspot cycle.

Balmer series (133) Spectral lines in the visible and near-ultraviolet spectrum of hydrogen produced by transitions whose lowest orbit is the second.

barred spiral galaxy (334) A spiral galaxy with an elongated nucleus resembling a bar from which the arms originate.

big bang (373) The theory that the universe began with a violent explosion from which the expanding universe of galaxies eventually formed.

big rip (388) The possible fate of the universe if dark energy increases rapidly and the expansion of space-time pulls galaxies, stars, and ultimately atoms apart.

binary star (178) One of a pair of stars that orbit around their common center of mass.

binding energy (124) The energy needed to pull an electron away from its atom.

biological evolution (402) The combined effect of variation and natural selection resulting in new species arising and existing species adapting to the environment or becoming extinct. Also called Darwinian evolution.

bipolar flow (223) Oppositely directed jets of gas ejected by some protostellar objects.

birth line (220) In the H-R diagram, the line above the main sequence where protostars first become visible.

blackbody radiation (127) Radiation emitted by a hypothetical perfect radiator; the spectrum is continuous, and the wavelength of maximum emission depends only on the body's temperature.

black dwarf (259) The end state of a white dwarf that has cooled to low temperature.

black hole (291) A mass that has collapsed to such a small volume that its gravity prevents the escape of all radiation; also, the volume of space from which radiation may not escape.

blueshift (138) The shortening of the wavelengths of light observed when the source and observer are approaching each other.

Bok globule (216) Small, dark, and dense interstellar cloud only about 1 ly in diameter that contains 10 to 1000 M_{\odot} of gas and dust; thought to be related to star formation.

bright-line spectrum (132) See *emission spectrum*.

brown dwarf (237) A very cool, low-luminosity star whose mass is not sufficient to ignite nuclear fusion.

butterfly diagram (155) See *Maunder butterfly diagram*.

calibrate (306) To make observations of reference objects, checks on instrument performance,

calculations of units conversions, etc. needed to completely understand measurements of unknown quantities.

Cambrian explosion (405) The sudden appearance of complex life forms at the beginning of the Cambrian period 0.6 to 0.5 billion years ago. Cambrian rocks contain the oldest easily identifiable fossils.

carbonaceous chondrite (552) Stony meteorite that contains both chondrules and volatiles. These may be the least altered remains of the solar nebula still present in the solar system.

carbon deflagration (271) The process in which the carbon in a white dwarf is completely consumed by nuclear fusion, producing a type Ia supernova explosion.

carbon–nitrogen–oxygen (CNO) cycle (226) A series of nuclear reactions that use carbon as a catalyst to combine four hydrogen atoms to make one helium atom plus energy; effective in stars more massive than the sun.

Cassegrain focus (110) The optical design of a reflecting telescope in which the secondary mirror reflects light back down the tube through a hole in the center of the objective mirror.

celestial equator (17) The imaginary line around the sky directly above Earth's equator.

celestial sphere (18) An imaginary sphere of very large radius surrounding Earth to which the planets, stars, sun, and moon seem to be attached.

center of mass (85) The balance point of a body or system of bodies.

central bulge (309) The spheroidal cloud of stars at the center of most spiral galaxies including our Milky Way Galaxy.

Cepheid variable star (247) Variable star with a period of 1 to 60 days; the period of variation is related to luminosity.

Chandrasekhar limit (262) The maximum mass of a white dwarf, about $1.4 M_{\odot}$; a white dwarf of greater mass cannot support itself and will collapse.

charge-coupled device (CCD) (113) An electronic device consisting of a large array of light-sensitive elements used to record very faint images.

chemical evolution (405) The chemical process that led to the growth of complex molecules on the primitive Earth. This did not involve the reproduction of molecules.

chromatic aberration (102) A distortion found in refracting telescopes because lenses focus different colors at slightly different distances. Images are consequently surrounded by color fringes.

chromosome (401) One of the bodies in a cell that contains the DNA carrying genetic information.

chromosphere (41) Bright gases just above the photosphere of the sun.

circular velocity (84) The velocity required to remain in a circular orbit about a body.

circumpolar constellation (19) Any of the constellations so close to the celestial pole that they never set (or never rise) as seen from a given latitude.

closed orbit (85) An orbit that returns to its starting point; a circular or elliptical orbit. (See *open orbit*.)

closed universe (381) A model universe in which the average density is great enough to stop the expansion and make the universe contract.

cluster method (340) The method of determining the masses of galaxies based on the motions of galaxies in a cluster.

CNO cycle (226) See *carbon–nitrogen–oxygen cycle*.

cocoon (214) The cloud of gas and dust around a contracting protostar that conceals it at visible wavelengths.

cold dark matter (383) Invisible matter in the universe composed by heavy, slow-moving particles such as WIMPs.

compact object (259) A star that has collapsed to form a white dwarf, neutron star, or black hole.

comparison spectrum (113) A spectrum of known spectral lines used to identify unknown wavelengths in an object's spectrum.

conservation of energy law (233) One of the basic laws of stellar structure. The amount of energy flowing out of the top of a shell must equal the amount coming in at the bottom plus whatever energy is generated within the shell.

conservation of mass law (233) One of the basic laws of stellar structure. The total mass of the star must equal the sum of the masses of the shells, and the mass must be distributed smoothly throughout the star.

constellation (12) One of the stellar patterns identified by name, usually of mythological gods, people, animals, or objects; also, the region of the sky containing that star pattern.

continuous spectrum (132) A spectrum in which there are no absorption or emission lines.

convection (145) Circulation in a fluid driven by heat; hot material rises, and cool material sinks.

convective zone (152) The region inside a star where energy is carried outward as rising hot gas and sinking cool gas.

cooling line (214) A far-infrared spectral emission line that releases energy from the insides of contracting protostellar clouds, allowing rapid contraction to continue.

corona (41) The faint outer atmosphere of the sun; composed of low-density, very hot, ionized gas. On Venus, round networks of fractures and ridges up to 1000 km in diameter.

coronagraph (146) A telescope designed to photograph the inner corona of the sun.

coronal gas (204) Extremely high-temperature, low-density gas in the interstellar medium.

coronal hole (163) An area of the solar surface that is dark at X-ray wavelengths; thought to be associated with divergent magnetic fields and the source of the solar wind.

coronal mass ejection (CME) (163) Gas trapped in the sun's magnetic field.

cosmic microwave background radiation (375) Radiation from the hot clouds of the big bang ex-

pllosion. Because of its large redshift, it appears to come from a body whose temperature is only 2.7 K.

cosmic ray (119) A subatomic particle traveling at tremendous velocity that strikes Earth's atmosphere from space.

cosmological constant (Λ) (387) Einstein's constant that represents a repulsion in space to oppose gravity.

cosmological principle (380) The assumption that any observer in any galaxy sees the same general features of the universe.

cosmologist (371) An astronomer or physicist whose research focuses on the overall properties of the universe and its origin.

cosmology (370) The study of the nature, origin, and evolution of the universe.

Coulomb barrier (152) The electrostatic force of repulsion between bodies of like charge; commonly applied to atomic nuclei.

Coulomb force (124) The repulsive force between particles with like electrostatic charge.

critical density (382) The average density of the universe needed to make its curvature flat.

dark age (378) The period of a few hundred million years during which the universe expanded in darkness. Extends from soon after the big bang glow faded into the infrared to the formation of the first stars.

dark energy (387) The energy of empty space that drives the acceleration of the expanding universe.

dark-line spectrum (132) See *absorption spectrum*.

dark matter (311) Nonluminous material that is detected only by its gravitational influence.

dark nebula (195) A nonluminous cloud of gas and dust visible because it blocks light from more distant stars and nebulae.

deferent (57) In the Ptolemaic theory, the large circle around Earth along which the center of the epicycle moved.

degenerate matter (241) Extremely high-density matter in which pressure no longer depends on temperature, due to quantum mechanical effects.

density (137) The amount of matter per unit volume in a material; measured in grams per cubic centimeter, for example.

density wave theory (315) Theory proposed to account for spiral arms as compressions of the interstellar medium in the disk of the galaxy.

deuterium (151) An isotope of hydrogen in which the nucleus contains a proton and a neutron.

diamond ring effect (41) A momentary phenomenon seen during some total solar eclipses when the ring of the corona and a bright spot of photosphere resemble a large diamond set in a silvery ring.

differential rotation (158) The rotation of a body in which different parts of the body have different periods of rotation; this is true of the sun, the Jovian planets, and the disk of the galaxy.

diffraction fringe (104) Blurred fringe surrounding any image caused by the wave

properties of light. Because of this, no image detail smaller than the fringe can be seen.

disk component (308) All material confined to the plane of the galaxy.

distance indicator (337) Object whose luminosity or diameter is known; used to find the distance to a star cluster or galaxy.

distance modulus ($m_V - M_V$) (172) The difference between the apparent and absolute magnitude of a star; a measure of how far away the star is.

distance scale (338) The combined calibration of distance indicators used by astronomers to find the distances to remote galaxies.

DNA (deoxyribonucleic acid) (400) The long carbon-chain molecule that records information to govern the biological activity of the organism. DNA carries the genetic data passed to offspring.

Doppler effect (137) The change in the wavelength of radiation due to relative radial motion of source and observer.

double-exhaust model (360) The theory that double radio lobes are produced by pairs of jets emitted in opposite directions from the centers of active galaxies.

double-lobed radio galaxy (358) A galaxy that emits radio energy from two regions (lobes) located on opposite sides of the galaxy.

Drake equation (412) A formula for the number of communicative civilizations in our galaxy.

dust (type II) tail (568) The tail of a comet formed of dust blown outward by the pressure of sunlight. (See *gas tail*.)

dynamo effect (158) The process by which a rotating, convecting body of conducting matter, such as Earth's core, can generate a magnetic field.

east point (18) The point on the eastern horizon exactly halfway between the north point and the south point; exactly east.

eccentric (55) (noun) An off-center circular path. (Note that the *adjective* "eccentric" refers instead to an ellipse that is not a perfect circle.)

eccentricity (e) (64) A measure of the flattening of an ellipse. An ellipse of $e = 0$ is circular. The closer to 1 e becomes, the more flattened the ellipse.

eclipse season (43) That period when the sun is near a node of the moon's orbit and eclipses are possible.

eclipse year (44) The time the sun takes to circle the sky and return to a node of the moon's orbit; 346.62 days.

eclipsing binary (183) A binary star system in which the stars eclipse each other.

ecliptic (21) The apparent path of the sun around the sky.

electromagnetic radiation (99) Changing electric and magnetic fields that travel through space and transfer energy from one place to another—for example, light, radio waves, and the like.

electron (123) Low-mass atomic particle carrying a negative charge.

ellipse (64) A closed curve enclosing two points (foci) such that the total distance from one focus

to any point on the curve back to the other focus equals a constant.

elliptical galaxy (334) A galaxy that is round or elliptical in outline; it contains little gas and dust, no disk or spiral arms, and few hot, bright stars.

emission line (132) A bright line in a spectrum caused by the emission of photons from atoms.

emission nebula (194) A cloud of glowing gas excited by ultraviolet radiation from hot stars.

emission (bright-line) spectrum (132) A spectrum containing emission lines.

energy (86) The capacity of a natural system to perform work—for example, thermal energy.

energy level (126) One of a number of states an electron may occupy in an atom, depending on its binding energy.

energy transport (225) The law of energy transport states that energy must flow from hot regions to cool regions by conduction, convection, or radiation.

enzyme (400) Special protein that controls processes in an organism.

epicycle (57) The small circle followed by a planet in the Ptolemaic theory. The center of the epicycle follows a larger circle (deferent) around Earth.

equant (57) The point off-center in the deferent from which the center of the epicycle appears to move uniformly.

equatorial mounting (111) A telescope mounting that allows motion parallel to and perpendicular to the celestial equator.

escape velocity (V_e) (85) The initial velocity an object needs to escape from the surface of a celestial body.

evening star (24) Any planet visible in the sky just after sunset.

event horizon (292) The boundary of the region of a black hole from which no radiation may escape. No event that occurs within the event horizon is visible to a distant observer.

excited atom (126) An atom in which an electron has moved from a lower to a higher orbit.

expanding universe (372) The idea, supported by observed redshifts of galaxies, that space is stretching, carrying galaxies and galaxy clusters away from each other.

extremophile (407) An organism that can survive in an extreme environment, for example, very low or high temperatures, high acidity, extreme dryness, etc.

eyepiece (102) A short-focal-length lens used to enlarge the image in a telescope; the lens nearest the eye.

false-color image (113) A representation of graphical data in which the colors are altered or added to reveal details.

field (81) A way of explaining action at a distance; a particle produces a field of influence (gravitational, electric, or magnetic) to which another particle in the field responds.

field of view (2) The area visible in an image; usually given as the diameter of the region.

filament (162, 389) (1) On the sun, a prominence seen silhouetted against the solar surface. (2) A linear region containing many galaxies and galaxy clusters, part of the large-scale structure of the universe.

filtergram (146) An image (usually of the sun) taken in the light of a specific region of the spectrum—for example, an H-alpha filtergram.

flare (163) A violent eruption on the sun's surface.

flatness problem (384) In cosmology, the circumstance that the early universe must have contained almost exactly the right amount of matter to close space-time (to make space-time flat).

flat universe (381) A model of the universe in which space-time is not curved.

flocculent (316) Woolly, fluffy; used to refer to certain galaxies that have a woolly appearance.

flux (15, 171) A measure of the flow of energy onto or through a surface. Usually applied to light.

focal length (102) The distance from a lens to the point where it focuses parallel rays of light.

forbidden line (196) A spectral line that does not occur in the laboratory because it depends on an atomic transition that is highly unlikely.

free-fall collapse (213) The early contraction of a gas cloud to form a star during which internal pressure is too low to resist contraction.

frequency (99) The number of times a given event occurs in a given time; for a wave, the number of cycles that pass the observer in 1 second.

galactic cannibalism (348) The theory that large galaxies absorb smaller galaxies.

galactic corona (311) The low-density extension of the halo of a galaxy; now suspected to extend many times the visible diameter of the galaxy.

galactic fountain (323-324) A region of the galaxy's disk in which gas heated by supernova explosions throws gas out of the disk where it can fall back and spread metals through the disk.

galaxy (5) A very large collection of gas, dust, and stars orbiting a common center of mass. The sun and Earth are located in the Milky Way Galaxy.

Galilean moons (68) The four largest satellites of Jupiter, named after their discoverer, Galileo.

gamma-ray burst (297) A sudden burst of gamma rays thought to be associated with neutron stars and black holes.

gene (401) A unit of DNA containing genetic information that influences a particular inherited trait.

general theory of relativity (92) Einstein's more sophisticated theory of space and time, which describes gravity as a curvature of space-time.

geocentric universe (54) A model universe with Earth at the center, such as the Ptolemaic universe.

geosynchronous satellite (84) An Earth satellite in an eastward orbit whose period is 24 hours. A satellite in such an orbit remains above the same spot on Earth's surface.

giant (175) Large, cool, highly luminous star in the upper right of the H–R diagram, typically 10 to 100 times the diameter of the sun.

giant molecular cloud (204) Very large, cool cloud of dense gas in which stars form.

globular cluster (248) A star cluster containing 50,000 to 1 million stars in a sphere about 75 ly in diameter; generally old, metal-poor, and found in the spherical component of the galaxy.

grand design (316) Galaxy with a high-contrast simple 2-arm spiral pattern.

grand unified theory (GUT) (385) Theory that attempts to unify (describe in a similar way) the electromagnetic, weak, and strong forces of nature.

granulation (144) The fine structure visible on the solar surface caused by rising currents of hot gas and sinking currents of cool gas below the surface.

grating (113) A piece of material in which numerous microscopic parallel lines are scribed; light encountering a grating is dispersed to form a spectrum.

gravitational lensing (343) The effect of the focusing of light from a distant galaxy or quasar by an intervening galaxy to produce multiple images of the distant body.

gravitational radiation (286) As predicted by general relativity, expanding waves in a gravitational field that transport energy through space.

gravitational redshift (293) The lengthening of the wavelength of a photon due to its escape from a gravitational field.

ground state (126) The lowest permitted electron orbit in an atom.

habitable zone (410) The region around a star within which an orbiting planet can have surface temperatures allowing liquid water.

halo (309) The spherical region of a spiral galaxy containing a thin scattering of stars, star clusters, and small amounts of gas.

heat (127) Energy flowing from a warm body to a cool body by the agitation of particles such as atoms or molecules.

heliocentric universe (58) A model of the universe with the sun at the center, such as the Copernican universe.

helioseismology (148) The study of the interior of the sun by the analysis of its modes of vibration.

helium flash (242) The explosive ignition of helium burning that takes place in some giant stars.

Herbig–Haro object (223) A small nebula associated with star formation that varies irregularly in brightness.

Hertzsprung–Russell (H–R) diagram (174) A plot of the intrinsic brightness versus the surface temperature of stars; it separates the effects of temperature and surface area on stellar luminosity; commonly absolute magnitude versus spectral type but also luminosity versus surface temperature or color.

H I cloud (202) An interstellar cloud of neutral hydrogen.

H II region (194) A region of ionized hydrogen around a hot star.

homogeneous (380) The property of being uniform. In cosmology, the characteristic of the universe in which, on the large scale, matter is uniformly spread through the universe.

horizon (18) The line that marks the apparent intersection of Earth and the sky.

horizon problem (384) In cosmology, the circumstance that the primordial background radiation seems much more isotropic than could be explained by the standard big bang theory.

horizontal branch (249) In the H–R diagram of a globular cluster, the sequence of stars extending from the red giants toward the blue side of the diagram; includes RR Lyrae stars.

horoscope (25) A chart showing the positions of the sun, moon, planets, and constellations at the time of a person's birth; used in astrology to attempt to read character or foretell the future.

hot dark matter (383) Invisible matter in the universe composed of low-mass, high-velocity particles such as neutrinos.

hot spot (360) In radio astronomy, a bright spot in a radio lobe.

H–R diagram (174) See *Hertzsprung–Russell diagram*.

Hubble constant (H) (339) A measure of the rate of expansion of the universe; the average value of velocity of recession divided by distance; about 70 km/s/megaparsec.

Hubble law (339) The linear relation between the distance to a galaxy and its radial velocity.

Hubble time (374) An upper limit on the age of the universe derived from the Hubble constant.

hydrostatic equilibrium (225) The balance between the weight of the material pressing downward on a layer in a star and the pressure in that layer.

hypernova (297) The explosion produced as a very massive star collapses into a black hole; thought to be responsible for at least some gamma-ray bursts.

hypothesis (66) A conjecture, subject to further tests, that accounts for a set of facts.

inflationary universe (385) A version of the big bang theory that includes a rapid expansion when the universe was very young.

infrared radiation (100) Electromagnetic radiation with wavelengths intermediate between visible light and radio waves.

inner Lagrangian point (263) The point of gravitational equilibrium between two orbiting stars through which matter can flow from one star to the other.

instability strip (250) The region of the H–R diagram in which stars are unstable to pulsation; a star passing through this strip becomes a variable star.

intercloud medium (202) The hot, low-density gas between cooler clouds in the interstellar medium.

interferometry (112) The observing technique in which separated telescopes combine to produce a virtual telescope with the resolution of a much-larger-diameter telescope.

interstellar absorption line (197) One of the dark lines in some stellar spectra that are formed by interstellar gas.

interstellar dust (196) Microscopic solid grains in the interstellar medium.

interstellar extinction (196) The dimming of starlight by gas and dust in the interstellar medium.

interstellar medium (ISM) (193) The gas and dust distributed between the stars.

interstellar reddening (196) The process in which dust scatters blue light out of starlight and makes the stars look redder.

intrinsic brightness (171) The true brightness of an object independent of its distance. Also referred to as luminosity.

intrinsic variable star (247) A variable star driven to pulsate by processes in its interior.

inverse square law (81) The rule that the strength of an effect (such as gravity) decreases in proportion as the distance squared increases.

ion (124) An atom that has lost or gained one or more electrons.

ionization (124) The process in which atoms lose or gain electrons.

irregular galaxy (335) A galaxy with a chaotic appearance, large clouds of gas and dust, and both population I and population II stars, but without spiral arms.

island universe (332) An older term for a galaxy.

isotopes (124) Atoms that have the same number of protons but a different number of neutrons.

isotropic (380) The conditions of being uniform in all directions. In cosmology, the characteristic of the universe by which, in its general properties, looks the same in every direction.

joule (J) (86) A unit of energy equivalent to a force of 1 newton acting over a distance of 1 meter; 1 joule per second equals 1 watt of power.

Kelvin temperature scale (127) The temperature, in Celsius (centigrade) degrees, measured above absolute zero.

Keplerian motion (311) Orbital motion in accord with Kepler's laws of planetary motion.

kiloparsec (kpc) (303) A unit of distance equal to 1000 pc, or 3260 ly.

kinetic energy (86) Energy of motion. Depends on mass and velocity of a moving body.

Kirchhoff's laws (132) A set of laws that describe the absorption and emission of light by matter.

Lagrangian point (263) Point of stability in the orbital plane of a binary star system, planet, or moon. One is located 60° ahead and one 60° be-

hind the orbiting bodies; another is located between the orbiting bodies.

large-scale structure (389) The distribution of galaxy clusters and superclusters in walls and filaments surrounding voids mostly empty of galaxies.

L dwarf (135) A type of star that is even cooler than the M stars.

light curve (183) A graph of brightness versus time commonly used in analyzing variable stars and eclipsing binaries.

light-gathering power (103) The ability of a telescope to collect light; proportional to the area of the telescope objective lens or mirror.

lighthouse model (282) The explanation of a pulsar as a spinning neutron star sweeping beams of radio radiation around the sky.

light pollution (106) The illumination of the night sky by waste light from cities and outdoor lighting, which prevents the observation of faint objects.

light-year (ly) (4) The distance light travels in one year.

limb (145) The edge of the apparent disk of a body, as in “the limb of the moon.”

limb darkening (145) The decrease in brightness of the sun or other body from its center to its limb.

line of nodes (44) The line across an orbit connecting the nodes; commonly applied to the orbit of the moon.

local bubble or void (205) A region of high-temperature, low-density gas in the interstellar medium in which the sun happens to be located.

look-back time (338) The amount by which you look into the past when you look at a distant galaxy; a time equal to the distance to the galaxy in light-years.

luminosity (L) (172) The total amount of energy a star radiates in 1 second.

luminosity class (176) A category of stars of similar luminosity; determined by the widths of lines in their spectra.

lunar eclipse (33) The darkening of the moon when it moves through Earth’s shadow.

Lyman series (133) Spectral lines in the ultraviolet spectrum of hydrogen produced by transitions whose lowest orbit is the ground state.

magnetar (297) A class of neutron stars that have exceedingly strong magnetic fields; thought to be responsible for soft gamma-ray repeaters.

magnetic carpet (147) The widely distributed, low-level magnetic field extending up through the sun’s visible surface.

magnifying power (105) The ability of a telescope to make an image larger.

magnitude–distance formula (172) The mathematical formula that relates the apparent magnitude and absolute magnitude of a star to its distance.

magnitude scale (14) The astronomical brightness scale; the larger the number, the fainter the star.

main sequence (175) The region of the H–R diagram running from upper left to lower right, which includes roughly 90 percent of all stars.

mass (79) A measure of the amount of matter making up an object.

mass–luminosity relation (188) The more massive a star is, the more luminous it is.

Maunder butterfly diagram (155) A graph showing the latitude of sunspots versus time; first plotted by W. W. Maunder in 1904.

Maunder minimum (155) A period of less numerous sunspots and other solar activity from 1645 to 1715.

megaparsec (Mpc) (336) A unit of distance equal to 1 million pc.

metal (319) In astronomical usage, any atom heavier than helium.

metastable level (196) An atomic energy level from which an electron takes a long time to decay; responsible for producing forbidden lines.

Milankovitch hypothesis (26) The hypothesis that small changes in Earth’s orbital and rotational motions cause the ice ages.

Milky Way (6) The hazy band of light that circles the sky, produced by the combined light of billions of stars in our Milky Way Galaxy.

Milky Way Galaxy (6) The spiral galaxy containing the sun; visible at night as the Milky Way.

Miller experiment (403) An experiment that reproduced the conditions under which life began on Earth and amino acids and other organic compounds were manufactured.

millisecond pulsar (288) A pulsar with a period of approximately a millisecond, a thousandth of a second.

molecular cloud (203) An interstellar gas cloud that is dense enough for the formation of molecules; discovered and studied through the radio emissions of such molecules.

molecule (124) Two or more atoms bonded together.

momentum (79) The tendency of a moving object to continue moving; mathematically, the product of mass and velocity.

monolithic collapse hypothesis (325) The hypothesis that the Milky Way Galaxy formed by gravitational collapse of a single large spinning cloud of gas. This hypothesis is now considered inadequate to explain many observed characteristics of the Galaxy.

morning star (24) Any planet visible in the sky just before sunrise.

multicellular (405) An organism composed of many cells.

mutant (402) Offspring born with altered DNA.

nadir (18) The point on the bottom of the sky directly under your feet.

nanometer (nm) (100) A unit of length equal to 10^{−9} m.

natural law (66) A conjecture about how nature works in which scientists have overwhelming confidence.

natural motion (77) In Aristotelian physics, the motion of objects toward their natural places—fire and air upward and earth and water downward.

natural selection (402) The process by which the best traits are passed on, allowing the most able to survive.

neap tide (87) Ocean tide of low amplitude occurring at first- and third-quarter moon.

nebula (193) A cloud of gas and dust in space.

nebular hypothesis (398) The proposal that the solar system formed from a rotating cloud of gas.

neutrino (151) A neutral, massless atomic particle that travels at or nearly at the speed of light.

neutron (123) An atomic particle with no charge and about the same mass as a proton.

neutron star (280) A small, highly dense star composed almost entirely of tightly packed neutrons; radius about 10 km.

Newtonian focus (110) The focal arrangement of a reflecting telescope in which a diagonal mirror reflects light out the side of the telescope tube for easier access.

node (43) A point where an object’s orbit passes through the plane of Earth’s orbit.

nonbaryonic matter (383) In cosmology, a suspected component of the dark matter composed of matter that does not contain protons and neutrons.

north celestial pole (18) The point on the celestial sphere directly above Earth’s North Pole.

north point (18) The point on the horizon directly below the north celestial pole; exactly north.

nova (264) From the Latin “new,” a sudden brightening of a star, making it appear as a “new” star in the sky; thought to be associated with eruptions on white dwarfs in binary systems.

nuclear fission (150) Reaction that splits nuclei into less massive fragments.

nuclear fusion (150) Reaction that joins the nuclei of atoms to form more massive nuclei.

nucleosynthesis (322) The production of elements heavier than helium by the fusion of atomic nuclei in stars and during supernovae explosions.

nucleus (of an atom) (123) The central core of an atom containing protons and neutrons; carries a net positive charge.

OB association (224) A loosely bound cluster of young stars having spectral types O and B, indicating a region of relatively recent star formation.

objective lens or mirror (101–102) The main optical element in an astronomical telescope. The large lens at the top of the telescope or large mirror at the bottom.

observable universe (372) The part of the universe that is visible from Earth’s location in space and time.

Olbers's paradox (371) The conflict between observation and theory as to why the night sky should or should not be dark.

opacity (226) The resistance of a gas to the passage of radiation.

open cluster (248) A cluster of 10 to 10,000 stars with an open, transparent appearance and stars not tightly grouped; usually relatively young and located in the disk of the galaxy.

open orbit (85) An orbit that does not return to its starting point; an escape orbit. (See *closed orbit*.)

open universe (381) A model universe in which the average density is less than the critical density needed to halt the expansion.

paradigm (61) A commonly accepted set of scientific ideas and assumptions.

parallax (56) The apparent change in the position of an object due to a change in the location of the observer. Astronomical parallax is measured in seconds of arc.

parsec (pc) (169) The distance to a hypothetical star whose parallax is one second of arc; 1 pc = 206,265 AU = 3.26 ly.

partial lunar eclipse (36) A lunar eclipse in which the moon does not completely enter Earth's shadow.

partial solar eclipse (38) A solar eclipse in which the moon does not completely cover the sun.

Paschen series (133) Spectral lines in the infrared spectrum of hydrogen produced by transitions whose lowest orbit is the third.

path of totality (39) The track of the moon's umbral shadow over Earth's surface. The sun is totally eclipsed as seen from within this path.

penumbra (33) The portion of a shadow that is only partially shaded.

penumbral lunar eclipse (37) A lunar eclipse in which the moon enters the penumbra of Earth's shadow but does not reach the umbra.

perigee (39) The orbital point of closest approach to Earth.

perihelion (23) The orbital point of closest approach to the sun.

period–luminosity relation (247) The relation between period of pulsation and intrinsic brightness among Cepheid variable stars.

permitted orbit (124) One of the energy levels in an atom that an electron may occupy.

photon (100) A quantum of electromagnetic energy; carries an amount of energy that depends inversely on its wavelength.

photosphere (41) The bright visible surface of the sun.

planet (3) A nonluminous object, larger than a comet or asteroid, that orbits a star.

planetary nebula (257) An expanding shell of gas ejected from a star during the latter stages of its evolution.

polar axis (111) In an equatorial telescope mounting, the axis which is parallel to Earth's axis of rotation.

poor cluster (345) An irregularly shaped cluster that contains fewer than 1000 galaxies, many spiral, and no giant ellipticals.

population I star (319) Star rich in atoms heavier than helium; nearly always a relatively young star found in the disk of the galaxy.

population II star (319) Star poor in atoms heavier than helium; nearly always a relatively old star found in the halo, globular clusters, or the nuclear bulge.

positron (151) The antiparticle of the electron.

potential energy (86) The energy a body has by virtue of its position. A weight on a high shelf has more potential energy than a weight on a low shelf.

precession (17) The slow change in the direction of Earth's axis of rotation; one cycle takes nearly 26,000 years.

pressure (203) A force exerted over a surface; expressed as force per unit area.

primary lens or mirror (101-102) The main optical element in an astronomical telescope. The large lens at the top of the telescope tube or the large mirror at the bottom.

prime focus (110) The point at which the objective mirror forms an image in a reflecting telescope.

primordial soup (404) The rich solution of organic molecules in Earth's first oceans.

prominence (41, 162) Eruption on the solar surface; visible during total solar eclipses.

proper motion (170) The rate at which a star moves across the sky; measured in seconds of arc per year.

protein (400) Complex molecule composed of amino acid units.

proton (123) A positively charged atomic particle contained in the nucleus of an atom; the nucleus of a hydrogen atom.

proton–proton chain (151) A series of three nuclear reactions that build a helium atom by adding together protons; the main energy source in the sun.

protostar (214) A collapsing cloud of gas and dust destined to become a star.

protostellar disk (220) A gas cloud around a forming star flattened by its rotation.

pseudoscience (25) A subject that claims to obey the rules of scientific reasoning but does not. Examples include astrology, crystal power, and pyramid power.

pulsar (282) A source of short, precisely timed radio bursts; thought to be a spinning neutron star.

pulsar wind (282) The flow of high-energy particles that carries most of the energy away from a spinning neutron star.

quantum mechanics (124) The study of the behavior of atoms and atomic particles.

quasar (quasi-stellar object, or QSO) (358) Small, powerful source of energy thought to be the active core of a very distant galaxy.

quintessence (387) The proposed energy of empty space that causes the acceleration of the expanding universe.

radial velocity (V_r) (139) That component of an object's velocity directed away from or toward Earth.

radiation pressure (224) The force exerted on the surface of a body by its absorption of light. Small particles floating in the solar system can be blown outward by the pressure of the sunlight.

radiative zone (152) The region inside a star where energy is carried outward as photons.

radio galaxy (356) A galaxy that is a strong source of radio signals.

radio interferometer (115) Two or more radio telescopes that combine their signals to achieve the resolving power of a larger telescope.

recombination (378) The stage within a million years of the big bang when the gas became transparent to radiation.

reconnection (163) The process in the sun's atmosphere by which opposing magnetic fields combine and release energy to power solar flares.

red dwarf (175) Cool, low-mass star on the lower main sequence.

redshift (138) The lengthening of the wavelengths of light seen when the source and observer are receding from each other.

reflecting telescope (101) A telescope that uses a concave mirror to focus light into an image.

reflection nebula (194) A nebula produced by starlight reflecting off dust particles in the interstellar medium.

refracting telescope (101) A telescope that forms images by bending (refracting) light with a lens.

reionization (378) The stage in the early history of the universe when ultraviolet photons from the first stars ionized the gas filling space.

resolving power (104) The ability of a telescope to reveal fine detail; depends on the diameter of the telescope objective.

retrograde motion (56) The apparent backward (westward) motion of planets as seen against the background of stars.

revolution (20) The motion of an object in a closed path about a point outside its volume; Earth revolves around the sun.

rich cluster (344) A cluster containing over 1000 galaxies, mostly elliptical, scattered over a volume about 3 Mpc in diameter.

ring galaxy (349) A galaxy that resembles a ring around a bright nucleus; thought to be the result of a head-on collision of two galaxies.

RNA (ribonucleic acid) (401) A long carbon-chain molecule that uses the information stored in DNA to manufacture complex molecules necessary to the organism.

Roche lobe (263) In a system with two bodies orbiting each other, the volume of space dominated by the gravitation of one of the bodies.

Roche surface (263) In a system with two bodies orbiting each other, the outer boundary of the volume of space dominated by the gravitation of one of the bodies.

rotation (20) The turning of a body about an axis that passes through its volume; Earth rotates on its axis.

rotation curve (311, 340) A graph of orbital velocity versus radius in the disk of a galaxy.

rotation curve method (340) The procedure for finding the mass of a galaxy from its rotation curve.

RR Lyrae variable star (247) Variable star with a period of 12 to 24 hours; common in some globular clusters.

Sagittarius A* (318) The powerful radio source located at the core of the Milky Way Galaxy.

saros cycle (44) An 18-year $11\frac{1}{3}$ -day period after which the pattern of lunar and solar eclipses repeats.

Schmidt-Cassegrain focus (110) The optical design of a reflecting telescope in which a thin correcting lens is placed at the top of a Cassegrain telescope.

Schwarzschild radius (R_s) (292) The radius of the event horizon around a black hole.

scientific argument (27) An honest, logical discussion of observations and theories intended to reach a valid conclusion.

scientific method (8) The reasoning style by which scientists test theories against evidence to understand how nature works.

scientific model (17) An intellectual concept designed to help you think about a natural process without necessarily being a conjecture of truth.

scientific notation (3) The system of recording very large or very small numbers by using powers of 10.

secondary mirror (110) In a reflecting telescope, the mirror that reflects the light to a point of easy observation.

seeing (104) Atmospheric conditions on a given night. When the atmosphere is unsteady, producing blurred images, the seeing is said to be poor.

self-sustaining star formation (316) The process by which the birth of stars compresses the surrounding gas clouds and triggers the formation of more stars; proposed to explain spiral arms.

semimajor axis (a) (64) Half of the longest axis of an ellipse.

SETI (411) Search for Extra-Terrestrial Intelligence.

Seyfert galaxy (356) An otherwise normal spiral galaxy with an unusually bright, small core that fluctuates in brightness; thought to indicate the core is erupting.

Shapley–Curtis Debate (332) The 1920 debate between Harlow Shapley and Heber Curtis over the nature of the spiral nebulae.

shock wave, or shock (205, 212) A sudden change in pressure that travels as an intense sound wave.

sidereal drive (111) The motor and gears on a telescope that turn it westward to keep it pointed at a star.

sidereal period (35) The period of rotation or revolution of an astronomical body relative to the stars.

singularity (291) The object of zero radius into which the matter in a black hole is thought to fall.

small-angle formula (39) The mathematical formula that relates an object's linear diameter and distance to its angular diameter.

solar constant (161) A measure of the energy output of the sun; the total solar energy striking 1 m^2 just above Earth's atmosphere in 1 second.

solar eclipse (38) The event that occurs when the moon passes directly between Earth and the sun, blocking your view of the sun.

solar system (3) The sun and the nonluminous objects that orbit it, including the planets, comets, and asteroids.

solar wind (147) Rapidly moving atoms and ions that escape from the solar corona and blow outward through the solar system.

south celestial pole (18) The point of the celestial sphere directly above Earth's South Pole.

south point (18) The point on the horizon directly above the south celestial pole; exactly south.

special theory of relativity (91) The first of Einstein's theories of relativity, which deals with uniform motion.

spectral class or type (131) A star's position in the temperature classification system O, B, A, F, G, K, and M. Based on the appearance of the star's spectrum.

spectral line (113) A dark or bright line that crosses a spectrum at a specific wavelength.

spectral sequence (131) The arrangement of spectral classes (O, B, A, F, G, K, M) ranging from hot to cool.

spectrograph (113) A device that separates light by wavelength to produce a spectrum.

spectroscopic binary (180) A star system in which the stars are too close together to be visible separately. You see a single point of light, and only by taking a spectrum can you determine that there are two stars.

spectroscopic parallax (178) The method of determining a star's distance by comparing its apparent magnitude with its absolute magnitude, as estimated from its spectrum.

spectrum (100) An arrangement of electromagnetic radiation in order of wavelength or frequency.

spherical component (309) The part of the galaxy including all matter in a spherical distribution around the center (the halo and nuclear bulge).

spicule (146) Small, flamelike projection in the chromosphere of the sun.

spiral arm (6) Long, spiral pattern of bright stars, star clusters, gas, and dust that extends from the center to the edge of the disk of spiral galaxies.

spiral galaxy (334) A galaxy with an obvious disk component containing gas; dust; hot, bright stars; and spiral arms.

spiral nebula (332) Nebulous object with a spiral appearance observed in early telescopes; later recognized as a spiral galaxy.

spiral tracer (313) Object used to map the spiral arms, for example O and B associations, open clusters, clouds of ionized hydrogen, and some types of variable stars.

spring tide (87) Ocean tide of high amplitude that occurs at full and new moon.

standard candle (337) Object of known brightness that astronomers use to find distance—for example, Cepheid variable stars and supernovae.

star (3) A celestial object composed of gas held together by its own gravity and supported by nuclear fusion occurring in its interior.

starburst galaxy (350) A bright blue galaxy in which many new stars are forming, thought to be caused by collisions between galaxies.

star-formation pillar (218) The column of gas produced when a dense core of gas protects the nebula behind it from the energy of a nearby hot star that is evaporating and driving away a star-forming nebula.

static (371) Unchanging in overall properties; opposite of evolving.

stellar model (234) A table of numbers representing the conditions in various layers within a star.

stellar parallax (p) (169) A measure of stellar distance. (See parallax.)

stellar wind (224) Hot gases blowing outward from the surface of a star. The equivalent for another star of the solar wind.

stromatolite (403) A layered fossil formation caused by ancient mats of algae or bacteria that build up mineral deposits season after season.

strong force (150) One of the four forces of nature; the strong force binds protons and neutrons together in atomic nuclei.

summer solstice (22) The point on the celestial sphere where the sun is at its most northerly point; also, the time when the sun passes this point, about June 22, and summer begins in the Northern Hemisphere.

sunspot (143) Relatively dark spot on the sun that contains intense magnetic fields.

supercluster (389) A cluster of galaxy clusters.

supergiant (175) Exceptionally luminous star, 10 to 1000 times the sun's diameter.

supergranule (145) A large granule on the sun's surface including many smaller granules.

supernova (268) A "new" star appearing in Earth's sky and lasting for a year or so before fading. Caused by the violent explosion of a star.

supernova remnant (273) The expanding shell of gas marking the site of a supernova explosion.

supernova (type Ia) (271) The explosion of a star caused by the collapse of a white dwarf that

has gained mass from its binary companion and exceeds the Chandrasekhar limit.

supernova (type Ib) (271) The explosion of a massive star that develops an iron core and collapses after it has lost its outer layers of hydrogen.

supernova (type I) (271) The violent explosion of a star in which the spectrum contains no hydrogen lines.

supernova (type II) (271) The explosion of a massive star that develops an iron core and collapses.

synchrotron radiation (272) Radiation emitted when high-speed electrons move through a magnetic field.

synodic period (35) The period of rotation or revolution of a celestial body with respect to the sun.

T association (224) A large, loosely bound group of T Tauri stars.

T dwarf (135) A very-low-mass star at the bottom end of the main sequence with a cool surface and a low luminosity.

temperature (127) A measure of the velocity of random motions among the atoms or molecules in a material.

theory (66) A system of assumptions and principles applicable to a wide range of phenomena that have been repeatedly verified.

thermal energy (127) The energy stored in an object as agitation among its atoms and molecules.

thermal pulse (257) Periodic eruptions in the helium fusion shell in an aging giant star; thought to aid in ejecting the surface layers of the stars to form planetary nebulae.

thermophile (407) A type of microorganism that thrives in high-temperature environments.

tidal tail (348) A long strand of gas, dust, and stars drawn out of a galaxy interacting gravitationally with another galaxy.

time dilation (293) The slowing of moving clocks or clocks in strong gravitational fields.

total lunar eclipse (36) A lunar eclipse in which the moon completely enters Earth's dark shadow.

total solar eclipse (38) A solar eclipse in which the moon completely covers the bright surface of the sun.

totality (36) The period during a solar eclipse when the sun's photosphere is completely hidden

by the moon, or the period during a lunar eclipse when the moon is completely inside the umbra of Earth's shadow.

transition (133) The movement of an electron from one atomic orbit to another.

triple alpha process (242) The nuclear fusion process that combines three helium nuclei (alpha particles) to make one carbon nucleus.

T Tauri star (222) Young star surrounded by gas and dust contracting toward the main sequence.

turnoff point (248) The point in an H–R diagram where a cluster's stars turn off the main sequence and move toward the red giant region, revealing the approximate age of the cluster.

21-cm radiation (198) Radio emission produced by cold, low-density hydrogen in interstellar space.

ultraluminous infrared galaxy (ULIRG) (350) A highly luminous galaxy so filled with dust that most of its energy escapes as infrared photons emitted by warmed dust.

ultraviolet radiation (100) Electromagnetic radiation with wavelengths shorter than visible light but longer than X-rays.

umbra (33) The region of a shadow that is totally shaded.

unified model (363) The attempt to explain the different kinds of active galaxies and quasars by a single model.

uniform circular motion (53) The classical belief that the perfect heavens could move only by the combination of constant motion along circular orbits.

variable star (247) A star whose brightness changes periodically.

velocity (79) A rate of travel that specifies both speed and direction.

velocity dispersion method (341) A method of finding a galaxy's mass by observing the range of velocities within the galaxy.

vernal equinox (22) The place on the celestial sphere where the sun crosses the celestial equator moving northward; also, the time of year when the sun crosses this point, about March 21, and spring begins in the Northern Hemisphere.

violent motion (77) In Aristotelian physics, motion other than natural motion. (See *natural motion*.)

visual binary (180) A binary star system in which the two stars are separately visible in the telescope.

void (339) A region containing relatively few galaxies, part of the large-scale structure of the universe.

water hole (411) The interval of the radio spectrum between the 21-cm hydrogen radiation and the 18-cm OH radiation, likely wavelengths to use in the search for extraterrestrial life.

wavelength (99) The distance between successive peaks or troughs of a wave; usually represented by λ .

wavelength of maximum intensity (λ_{max}) (128) The wavelength at which a perfect radiator emits the maximum amount of energy; depends only on the object's temperature.

weak force (150) One of the four forces of nature; the weak force is responsible for some forms of radioactive decay.

west point (18) The point on the western horizon exactly halfway between the north point and the south point; exactly west.

white dwarf (175) The remains of a dying star that has collapsed to the size of Earth and is slowly cooling off; at the lower left of the H–R diagram.

WIMP (383) Weakly Interacting Massive Particle, a hypothetical type of subatomic particle of which dark matter could be composed.

winter solstice (22) The point on the celestial sphere where the sun is farthest south; also, the time of year when the sun passes this point, about December 22, and winter begins in the Northern Hemisphere.

X-ray burster (288) An object that produces occasional X-ray flares. Thought to be caused by mass transfer in a closed binary star system.

Young Stellar Object (YSO) (220) A forming star in a late protostellar evolutionary stage that has lost its obscuring cocoon of gas and but is still contracting toward the main sequence.

Zeeman effect (155) The splitting of spectral lines into multiple components when the atoms are in a magnetic field.

zenith (18) The point directly overhead on the sky.

zero-age main sequence (ZAMS) (238) The locus in the H–R diagram where stars first reach stability as hydrogen-burning stars.

zodiac (25) The band around the sky centered on the ecliptic within which the planets move.

Answers to Even-Numbered Problems

Chapter 1:

2. 3475 km; 4. 1.1×10^8 km; 6. about 1.2 seconds; 8. 75,000 years; 10. about 27

Chapter 2:

2. 2; 4. 631; 6. A is brighter than B by a factor of 170; 8. 66.5° ; 113.5°

Chapter 3:

2. (a) full; (b) first quarter; (c) waxing gibbous; (d) waxing crescent; 4. 29.5 days later on about March 30th; 27.3 days later on about March 24th; 6. 6850 arc seconds or about 1.9° ; 8. (a) The moon won't be full until Oct. 17; (b) The moon will no longer be near the node of its orbit; 10. August 12, 2026 [July 10, 1972 + $3 \times (6585 \frac{1}{3} \text{ days})$]. In order to get August 12 instead of August 11, you must take into account the number of leap days in the interval.

Chapter 4:

2. Retrograde motion: Jupiter, Saturn, Uranus, Neptune; Never seen as crescents: Jupiter, Saturn, Uranus, Neptune; 4. $\sqrt{27} = 5.2$ years; 6. No. The ratio in the diagram is about 1.5.

Chapter 5:

2. The force of gravity on the moon is about $\frac{1}{6}$ the force of gravity on Earth; 4. 7350 m/s; 6. 5070 s (1 hr and 25 min); 8. The cannonball would move in an elliptical orbit with Earth's center at one focus of the ellipse; 10. 6320 s (1 hr and 45 min)

Chapter 6:

2. 3m; 4. Either Keck telescope has a light-gathering power that is 1.56 million times greater than the human eye; 6. No, his resolving power should have been about 5.8 seconds of arc at best; 8. 0.013 m (1.3 cm or about 0.5 in.); 10. about 50 cm (From 400 km above, a human is about 0.25 second of arc from shoulder to shoulder.)

Chapter 7:

2. 150 nm; 4. by a factor of 16; 6. 250 nm; 8. (a) B; (b) F; (c) M; (d) K; 10. about 0.58 nm

Chapter 8:

2. 730 km; 4. 9×10^{16} J; 6. 0.222 kg; 8. 400,000 years; 10. about 3.6 times

Chapter 9:

2. 63 pc; absolute magnitude is 2; 4. about B7; 6. about 1580 solar luminosities; 8. 160 pc; 10. a, c, c, d (use Figure 9-13 to determine the absolute magnitudes); 12. 3.69 days or 0.010 year; about 1.2 solar masses; about 0.67 and 0.53 solar mass; 14. 1.38×10^6 km, about the size of the sun

Chapter 10:

2. 60,000 nm; 4. 0.0001; 6. 1.5×10^6 years; 8. 4.2×10^{35} kg or 210,000 solar masses (*Note:* Each hydrogen molecule contains two H atoms.)

Chapter 11:

2. 25 km/s; 4. 3.0 km/s; 6. 9.5×10^{10} s (about 3000 years); 8. There are four ^1H nuclei in the figure. They are used in a series of reactions to build up nuclei from ^{12}C to ^{15}N . In the last reaction (with the ^{15}N) a ^{12}C and a ^4He are produced. Because the ^{12}C can be used in the next cycle, the net is four ^1H nuclei in with one ^4He nucleus out; 10. 7.9×10^{33} kg

Chapter 12:

2. about 9.8×10^6 years for a 16-solar-mass star; about 5.7×10^5 years for a 50-solar-mass star; 4. about 1×10^6 times less than present or about 1.4×10^{-6} g/cm³; 6. 2.4×10^{-9} or 1/420,000,000; 8. about 3 pc; 10. 3.04 minutes early after 1 year; 30.4 minutes early after 10 years

Chapter 13:

2. about 1.8 ly; 4. about 16,000 years old; 6. about 940 years ago (approximately AD 1060); 8. 2400 pc

Chapter 14:

2. 7.1×10^{25} J/s or about 0.19 solar luminosity; 4. 820 km/s (assuming mass is one solar mass); 6. about 11 seconds of arc; 8. about 490 seconds

Chapter 15:

2. about 16 percent; 4. 1.2×10^{14} s (3.9×10^6 yr); 6. overestimate by a factor of 1.58; 8. about 21 kpc; 10. 7.9×10^{10} solar masses; 12. about 1500 K

Chapter 16:

2. 2.6 Mpc; 4. 90 km/s, using the mass of the galaxy inside the sun's orbit from p. 308, or about 230 km/s, extrapolating to $r = 50$ pc the rotation curve on p. 309 that includes the observed effects of dark matter; 6. 29 Mpc; 8. 5.2×10^{15} s (1.6×10^8 yr); 10. 4.5×10^{41} kg (2.3×10^{11} solar masses)

Chapter 17:

2. 7.8×10^6 years; 4. 0.024 pc; 6. -28.5; 8. about 16th magnitude; 10. 0.16

Chapter 18:

2. 57 km/s/Mpc; 17.3 billion years; acceleration would decrease the age; 4. 1.6×10^{-27} kg/m³; 6. 76 km/s/Mpc

Chapter 19:

2. 8.8 cm; 0.88 mm; 4. approximately 1.5 solar masses, spectral type F2; 6. 380 km; 8. No correct answer; perhaps somewhere between pessimistic and optimistic estimates in Table 19-1, 2×10^{-5} and 10^7 , respectively

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Boldface page numbers indicate definitions of key terms.

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Flash Reference: Comparative Planetology

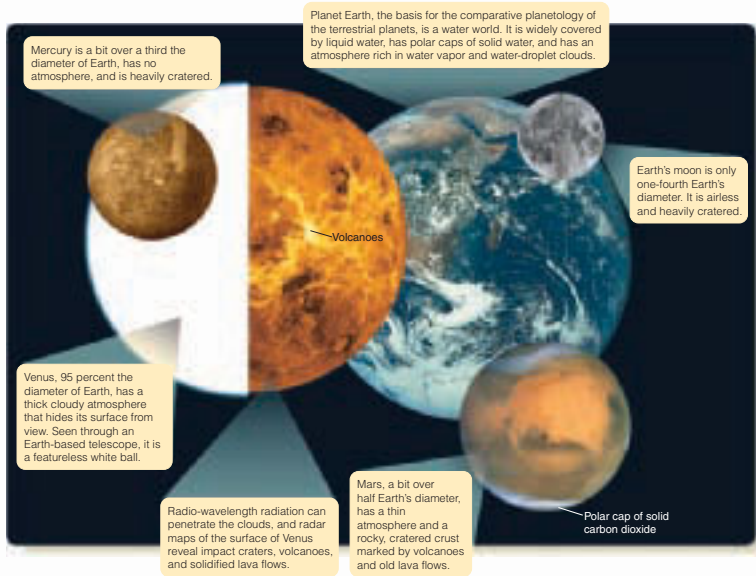
The terrestrial or Earthlike planets lie very close to the sun, and their orbits are hardly visible in a diagram that includes the outer planets.

Mercury, Venus, Earth and its moon, and Mars are small worlds made of rock and metal with little or no atmospheric gases.

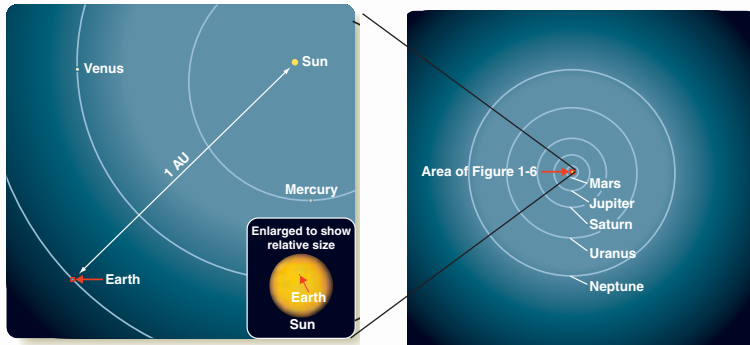
The outer worlds of our solar system orbit far from the sun. Jupiter, Saturn, Uranus, and Neptune are Jovian or Jupiter-like planets much bigger than Earth. They contain large amounts of low-density gases.

Pluto is one of a number of small, icy worlds orbiting beyond Neptune. Astronomers have concluded that Pluto is not really a planet and now refer to it as a dwarf planet.

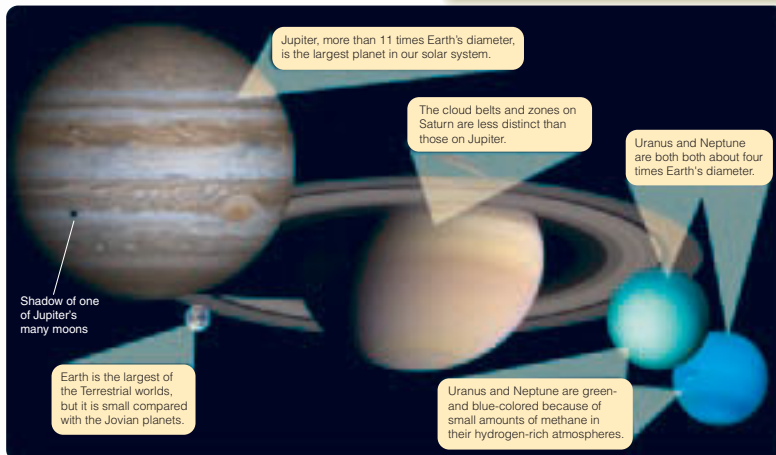
The Terrestrial Worlds



Planetary Orbits



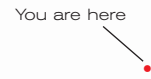
The Outer Worlds



Flash Reference: Arrows

This book is designed to use arrows to alert you to important concepts in diagrams and graphs. Some arrows point things out, but others represent motion, force, or even the flow of light. Look at arrows in the book carefully and use this Flash Reference card to catch all of the arrow clues.

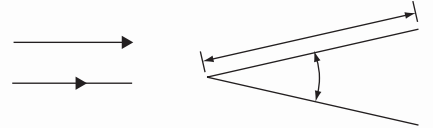
Point at things:



Force:



Process flow: **Measurement:**



Direction:

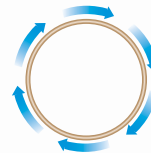


Radio waves, infrared, photons:

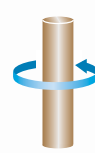


Motion:

Rotation 2-D



Rotation 3-D



Linear



Light flow:

Updated arrow style

