RECENT ADVANCES AND ISSUES IN Astronomy

Christopher G. De Pree
Kevin Marvel
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Preface

Writing a book entitled *Recent Advances and Issues in Astronomy* is a daunting task. Even casual observers who keep up to date with astronomy on the evening news and the local paper can appreciate that these are times of rapid change in the field. Dramatic new results are presented almost weekly in the *New York Times*. The progress of both observational and computing technologies have turbocharged astronomical research in the past two decades. Recent articles have even bemoaned the inability of astronomers to process and analyze all the data that we are receiving daily. Even the definition of the word *recent* is problematic. Should "recent" results be results from the last century? That might seem reasonable for a discipline that is already thousands of years old. Or should "recent" pertain to results of the last decade, or the last year? The most cursory discussion of the results of just the past few months of research in astronomy could easily fill a volume of this size—and still leave out many worthwhile projects. And in the time it takes to bind and distribute a book, many important results will be published in research journals.

Because it is impossible to cover all aspects of astronomy in a small book, we have attempted in this volume to give readers a sampling of the most important results and developments of the last decade. Of course, many results of the last decade were built upon predictions or observations made decades before. We believe the particular results, technologies, and developments we cover in this volume, along with the resources provided in some of the later chapters, will allow readers to remain abreast of truly *recent* issues and advances. In addition, we try to give readers an appreciation for the types of issues that are most important so that they can discriminate in the news between another pretty astronomical picture and a truly important astronomical result.

Chapters 1 and 2 present some of the most interesting results in astronomy in the past decade, with Chapter 1 concentrating on astronomical investigations, and Chapter 2 on the technologies and techniques that made them possible. Chapter 2, for example, provides an overview of observing instruments and technologies available to astronomers at the beginning of the twenty-first century.

Chapter 3 presents a picture of the interaction between astronomy and society. Because these interactions are not always obvious in astronomy, this chapter explores the interplay among astronomy, politics, and the environment. Chapter 4 contains primary sources and readings that amplify and enrich the topics discussed in Chapter 3.

Chapter 5 contains 39 biographies of men and women who have made unique contributions to the field in the past decade. The biographies include professional and amateur astronomers, young and old, women and men. Many of the astronomers in this chapter were involved in the research and observations discussed in Chapters 1 and 2.

Chapter 6 is entitled "Unsolved Problems, Unanswered Questions." As in most technical fields, the most enticing unsolved problems are ones that garner the most attention, and soon yield answers to persistent observations and clever theories. However, the problems presented in this chapter have remained mysteries for many decades and may hold their secrets for some time to come.

Chapters 7 and 8 give insight into the profession today and into the people who practice it. Chapter 7 contains narratives written by four trained astronomers, describing the career paths that they have taken, both in and out of astronomy. Chapter 8 provides a summary of funding and career statistics in astronomy.

Chapter 9 and 10 provide resources that allow readers to pursue a deeper understanding of topics of interest. Chapter 9 is an annotated listing of organizations in the field, and Chapter 10 is an annotated list of print and electronic resources. At book's end, a glossary briefly defines terms that may be unfamiliar to the nonexpert.

These pages will give readers a small but representative taste of the rich variety of topics and fields that comprise astronomy at the beginning of the twenty-first century.

Chapter One

Astronomy Today

Modern astronomers understand more about the universe than their predecessors could have ever imagined. The earliest astronomers apparently noticed that the motions of the sun, moon, planets, and stars were useful timekeeping aids, and most of our divisions of time (years, months, days) are related to celestial motions. Humanity also saw its stories reflected in the recognizable patterns in the sky and used the groupings of stars known as constellations as pictorial archives for their creation and evolution myths. Around the time of Sir Isaac Newton, (1643–1727) when it was first suggested that the same physical laws applied on Earth and in the heavens, astronomers began to do more than keep records. They began to ask how and why the objects in the sky moved in the ways that they did. Since the seventeenth century, astronomers have, with increasing speed, built an edifice of understanding about the universe. In this chapter, we discuss some of the most recent additions to that edifice, reviewing research that addresses some of the oldest questions that humanity has asked.

As mentioned in the preface, any selection of topics in a volume this size surely will be found wanting. We have, in this chapter, tried to include discoveries and investigations that have upset previously cherished ideas, have been discovered because of the advent of a new technology, have solved a long-standing dilemma, or have the potential for a long-term impact on our understanding of the way the universe works. However, even within the restrictions of these criteria, the chapter is meant to be representative rather than exhaustive.

PLANETARY SYSTEMS

Human speculation about other worlds has a long history. The Greek philosopher Heraclitus (c. 400 B.C.E.) claimed that the planets were divine but also that each planet was another world, like the Earth, with land and air. Heraclitus went further to suggest that the cosmos was infinite, a speculation that opened the possibility of an infinity of worlds. Theorists who study star formation and the gravitational contraction of solar-mass gas clouds have long proposed that planetary-mass objects should form naturally as a part of the collapse process. We have one clear example where this appears to have happened very successfully: the solar system. But as recently as 1995, there was no observational evidence of a planetary system around a sunlike star outside the system we inhabit. Now we have ample evidence that such planets exist; first, however, we will look at recent discoveries about our own solar system, then turn our attention to systems orbiting other stars.

Planetary Rovers, Probes, and Orbiters

The planet Mars has been at the center of some of the most dramatic failures and successes in planetary exploration of the past decade. The world's attention was transfixed as at no other time since the Apollo moon landing of 1969 when the Mars Pathfinder mission touched down on the surface of the planet on July 4, 1997, and transmitted images and weather information. It also released the Sojourner rover that moved on wheels slowly around the boulder-strewn landing site, making short excursions to explore nearby rocks. While this mission gave a detailed view of a small region of the surface of the planet, the Mars Global Surveyor (MGS) mission, launched on November 7, 1996, arrived at Mars on September 12 of the following year and has produced breathtaking high-resolution views of large portions of the Martian surface. And the information carried in these views has transformed our understanding of the Red Planet.

For years, planetary astronomers have speculated that the presence of what looked like dry riverbeds suggested that, at some time in the distant past, Mars was a wetter environment than it is now and that it had a more dense atmosphere. The images returned by the MGS (now in the "extended" phase of its mission since January 31, 2001) have much higher resolution than any previous images, in some cases showing surface details only a few meters across. These new images suggest the possibility that water has been present on the surface of Mars much more recently than previously thought. Some images show runoff that apparently crosses dunefields, presumably features that change on relatively brief timescales. In the summer of 2000, Michael Malin and Kenneth Edgett published a paper in *Science* that proposed that Mars had rather recently experienced groundwater seepage and surface runoff. Images like those from MGS present tantalizing evidence that while the surface of Mars is certainly devoid of running water now, there might be subterranean regions in which water may exist in liquid form. Visual evidence such as that presented by Malin and Edgett makes the case for conducting more sophisticated probing of the surface of Mars in the decades to come (Figure 1.1).

Part of the same mission, the Mars Orbiting Laser Altimeter (MOLA) has added a great deal to our understanding of the topography of Mars. Perhaps the most important result out of the MOLA mission is the realization of the incredible flatness of the northern hemisphere of the planet. MOLA has given astronomers the highest resolution topographic map of any planet other than the Earth, and MOLA imagery represents an improvement by a factor of 100 over the resolution of the old topographic maps. By combining altimeter readings with images of the surface, National Aeronautics and Space Administration (NASA) scientists have generated three-dimensional maps of the surface of Mars that will be useful to the planning of future missions and to geologists trying to piece together the geological history of the planet.

While the successes on Mars in the 1990s have been great, there have been some major disappointments in the past decade. The Mars Polar Lander, supposed to touch down on the surface of the planet on December 3, 1999, was never contacted and is believed to have crashed on the surface of the planet. In one of the most spectacular embarrassments of the space age, the Mars Climate Orbiter was lost apparently over a miscommunication about units between two engineering groups: One group used English units of measurement, and the other metric. On November 10, 1999, the Mars Climate Orbiter Mishap Investigation Board released their report admitting that the mission had failed because "thruster performance data in English units instead of metric units was used."

The other great success in planetary exploration of the late twentieth century must be the Galileo mission to Jupiter and its moons. Launched in October 1989, and having arrived at the largest planet in the solar system in December 1995, the Galileo mission was still sending back new scientific data in the summer of 2002. Galileo images of

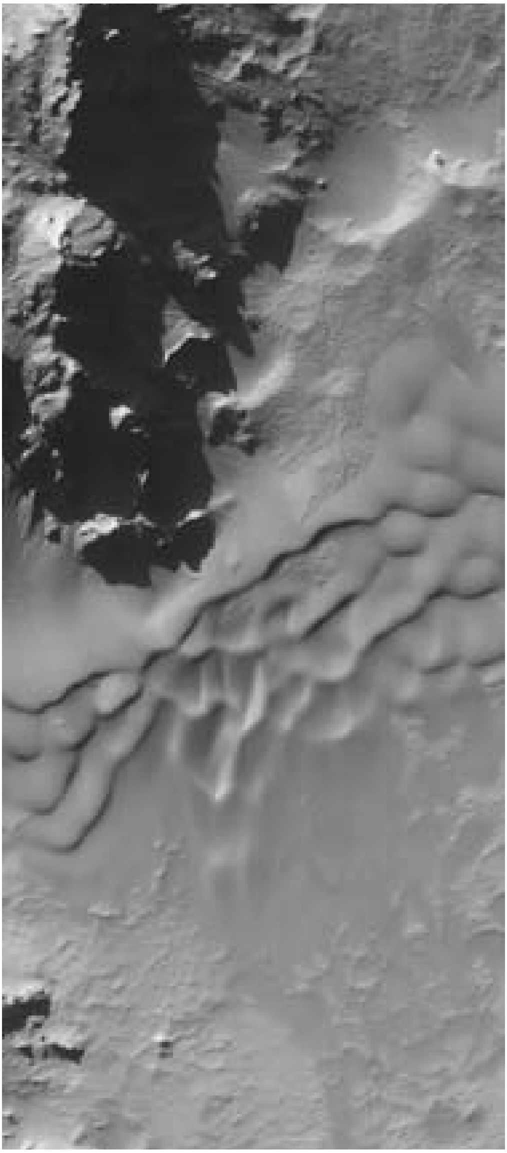

Figure 1.1. Detailed view of the Hale Crater basin, as imaged with the Mars Orbiter Camera (MOC). These mountains are located among the central peaks of the Hale Crater, a 136-km-diameter impact crater in the southern hemisphere of Mars. The largest of the peaks rises about 630 m above the basin surface. The windswept features are sand dunes and gullies. The image covers an area 3 km wide and picks out detail on the scale of 5 to 10 m. Courtesy of NASA, the Jet Propulsion Laboratory, and Malin Space Science Systems.

Jupiter and its moons have been breathtaking in their beauty and substantial in the number of contributions they have made to our understanding of this most important planet. Razor-sharp views of Europa, Ganymede, and Callisto provide evidence that these three moons possess subsurface saltwater oceans. Io's surface has been mapped extensively and with sufficient frequency to have revealed numerous events of volcanic activity. The mission was recently extended for a third time, since the instruments aboard have survived exposure to radiation levels well beyond their design specifications. The current mission extension is planned to end with a terminal entry into the Jovian atmosphere in August 2003.

Planet Hunting

While the presence of planets around other stars has been an accepted theory for at least a century, only in the last decade have we had any observational evidence to support the theory. The most successful technique used to search for planetary-mass objects around other stars has relied on the fact that any source of waves communicates information about its motion relative to the observer. Sound waves coming from a wobbling object have a periodic shift in their wavelength and hence their pitch. In the same way, light waves coming from a star also have a periodic shift in their wavelength if the source is moving back and forth relative to the observer. Planets orbiting their host stars produce a detectable wobble, especially if the planets are large enough (Jupiter sized) and close enough (within *1 AU* [astronomical unit]). The wobbles, of course, still exist for smaller planets and larger orbits; they just become more difficult to observe.

Planetary-mass objects were first discovered orbiting a dead massive star (called a pulsar) named PSR 1257 + 12. This object was discovered in 1992 by Aleksander Wolszczan and Dale Frail and was proposed to have two or three nearly Earth-mass-size objects orbiting it. Then, in 1995, astronomers Michel Mayor and Didier Queloz of Geneva Observatory discovered a giant planet around the sunlike star 51 Pegasi. Their announcement was soon confirmed, and in the past six years, "wobble" measurements have identified a large number of planets orbiting sunlike stars. Most recently, astronomers announced the first multiplanet system with nearly circular orbits, Jupiter-sized planets orbiting the star known as 47 Ursae Majoris (in the constellation more commonly known as the Big Dipper). The number of known planets increases sometimes weekly; as of May 2002, there were 78 confirmed extrasolar planetary systems listed on the University of California (UC) Planet Search Page (http://exoplanets.org/) (Figure 1.2). Only a year earlier, the number was half that amount.

The search for extrasolar planetary systems has enjoyed phenomenal success in the past few years. In the most fruitful search method, sometimes called the "Doppler shift" method, astronomers watch the *spectral lines* from a parent star move back and forth across the *electromagnetic spectrum* as the star's planets orbit and pull the star slightly back and forth. The wobble of spectral lines from no fewer than 78 solar-type stars has revealed the presence of one or more planets orbiting each of them. To cite one example, there are apparently three planets orbiting the star Upsilon Andromeda, with orbital periods between four days and four years and sizes from about the mass of the planet Jupiter to four times that mass. The size of the orbit is derived (using Kepler's third law) from the orbital period, and the lower limit to the planetary mass is determined from the velocity amplitude of the star's "wobble."

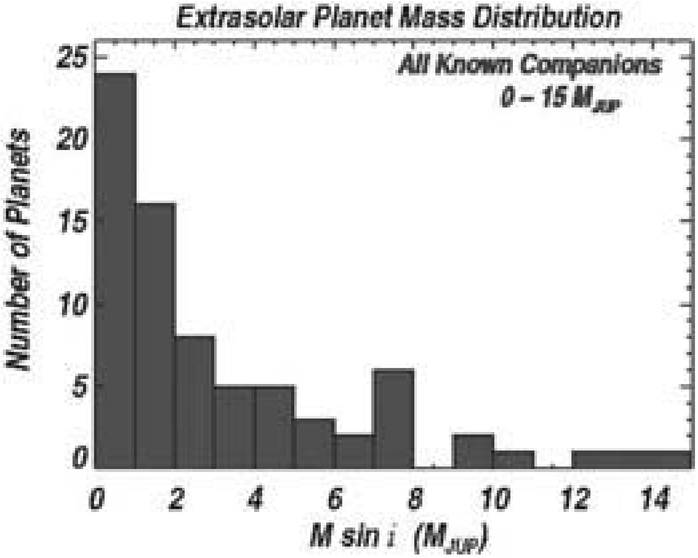

Figure 1.2. Extrasolar planet-mass distribution histogram. This diagram shows the number of extrasolar planets known within certain mass ranges, scaled to the mass of the largest planet in our solar system, Jupiter. Notice that there are fewer high-mass planets and more low-mass planets. Courtesy of Geoff Marcy, University of California, Berkeley.

One might well wonder why astronomers go to all this trouble, using spectral lines to detect signs of orbiting planets. Why not simply make images of these distant stars and *see* if there are any planets orbiting them?

Two issues compromise this seemingly simple method of observation. First, the planets orbiting a star have only a tiny fraction of the star's brightness. They "shine" only because they reflect a little bit of the light emitted by their parent star. Astronomers have compared trying to see a planet next to its parent star to trying to see a firefly next to a searchlight. Second, planets and their host star are very close to one another, and distinguishing (or resolving) a planet from its parent star can be very difficult, if not impossible, from the surface of the Earth. While the resolution of telescopes has increased dramatically with the advent of orbiting observatories (see Chapter 2), resolving a planet from its host star is still beyond our technical abilities. For these reasons, the Doppler shift technique has been by far the most successful method employed.

It is important to note, however, that some of the most promising missions in the coming decade or two are those that will attempt directly to image planets around other stars (Figures 1.3 and 1.4). NASA is planning a series of satellites, beginning with the Space Interferometry Mission (SIM) in 2006 and culminating with the Terrestrial Planet Finder (TPF) mission, which should be able to detect Earth-sized planets around nearby stars. Once astronomers have detected such planets, they will be able to gather light reflected off them and thereby study the atmospheres of the planets in question. It is possible that by the middle of this century, with the rapid development of optical and infrared interferometric techniques (see Chapter 2), astronomers will be able to image the disks of these planets with sufficient clarity to differentiate between continents and oceans. Many of the technologies necessary for TPF will be tested on currently active and planned telescopes, such as the Keck interferometer and the Next Generation Space Telescope (NGST). The launch for TPF is tentatively set for December 2010.

A mere five years ago, we knew of no planets orbiting sunlike stars—other than the nine in our own solar system. The character of the first extrasolar planetary system (51 Pegasi, discovered by Swiss astronomers Michel Mayor and Didier Queloz of the Geneva Observatory in 1995) came as a great surprise. The detected planet's size and orbit were not at all what was expected. It was a Jupiter-sized planet in a

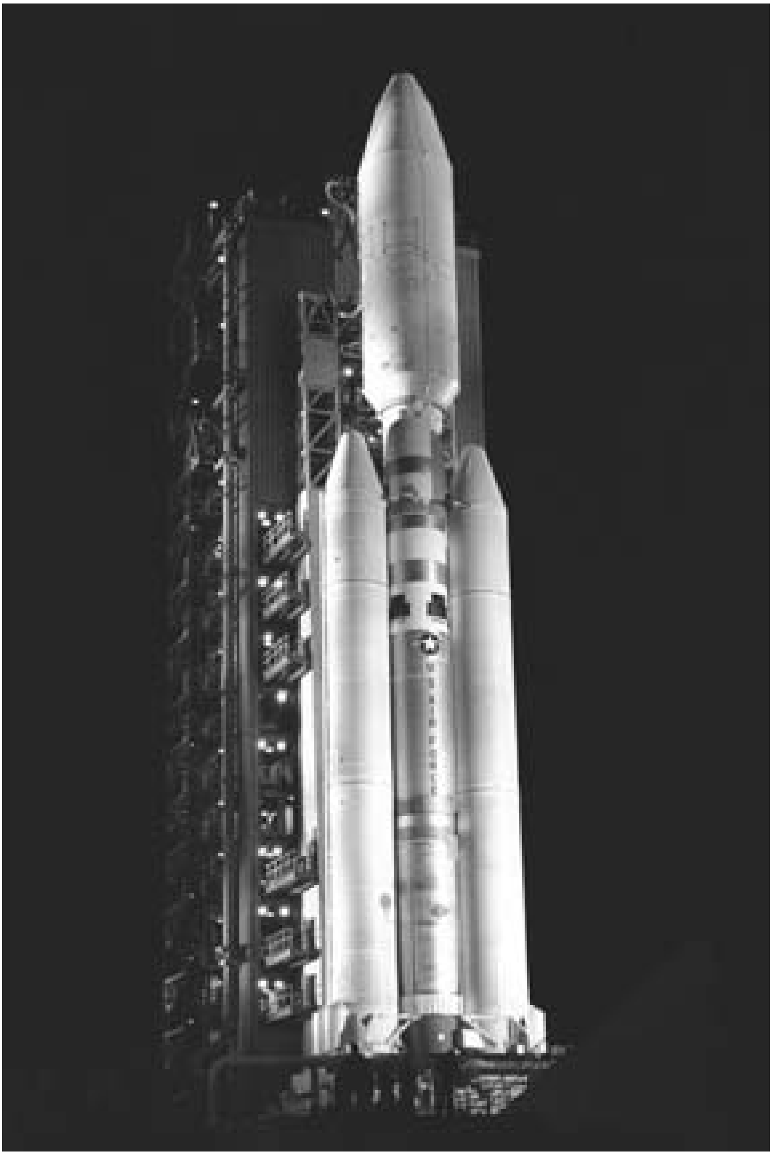

Figure 1.3. Many of the breathtaking images of the solar system that have been released in the past decade have come back from spacecraft sent to probe distant worlds. Here we see the launch vehicle for the Cassini-Huygens mission to Saturn and Titan—the Titan IVB/Centaur—at Cape Canaveral. The probe was launched successfully on October 15, 1998, and will arrive at Saturn in 2004. Courtesy of NASA.

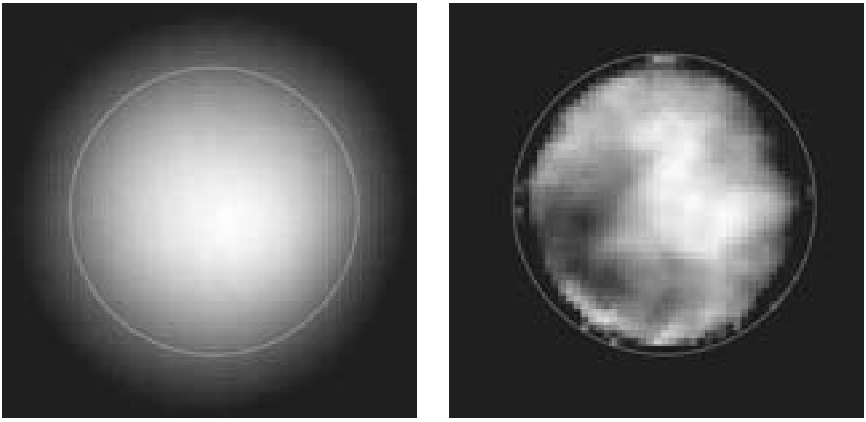

Figure 1.4. Comparison of Keck near-infrared images of the surface of Saturn's moon Titan taken with conventional techniques (*left*) and with speckle imaging techniques (*right*). The speckle image clearly shows detail (brighter regions being more reflective), whereas the conventional ground-based image shows a featureless disk. Speckle imaging, like interferometery, can overcome some limitations of ground-based optical telescopes by combining a large number of short exposures. Titan will be explored by the Cassini-Huygens missions that will arrive at Saturn in 2004. Courtesy of Lawrence Livermore National Laboratory.

sub-Mercury orbit! Thus the first extrasolar planetary system discovered around a solar-type star was nothing at all like our own solar system.

While there was some early controversy about the validity of the conclusions from the techniques employed by Geoff Marcy, Paul Butler, and others, those complaints seem to have quieted (Gray, 1997). The validity of the planet hunters' conclusions was decisively demonstrated by the recent prediction (and detection) of the dimming of the light of the star HD209458 as its planet passed in front of the star. If the orbits of distant planetary systems are oriented in such a way as to be "edge on"—that is, we look at the equator of the system instead of one of the poles—and the planets are sufficiently large, then when a planet passes in front of its star, it should reduce very slightly the amount of light that reaches us. Just such an effect was measured in 2000 by Henry et al. at precisely the time predicted from the period published by Marcy and Butler.

Until very recently, none of the systems discovered—from the multiple planetary system orbiting a pulsar to the many systems orbiting solar-type stars—have looked familiar. The recent discovery of the system in 47 Ursae Majoris is an exception. The paucity of any other solar-type systems has begun to raise the question: Are we as common as we once thought? The conventional wisdom for a few decades (at least among astronomers; biologists have generally been more circumspect) has been that there are so many possible sites for life to arise that the galaxy and the universe must be replete with it. However, recent developments in the understanding of the solar system, in conjunction with our discoveries about the nature of other planetary systems, suggest to some scientists that the Earth and the planetary system that we call home might be more rare than we had assumed (Figure 1.5).

In their book *Rare Earth* (2000), authors Peter Ward and Donald Brownlee go so far as to propose that far from being full of advanced civilizations, the galaxy might be a lonely place, with the complex life that we find on Earth a rare exception. In the 1960s, radio astronomer Frank Drake proposed a simple equation that allowed scientists to calculate (albeit based on a number of very uncertain values) the number

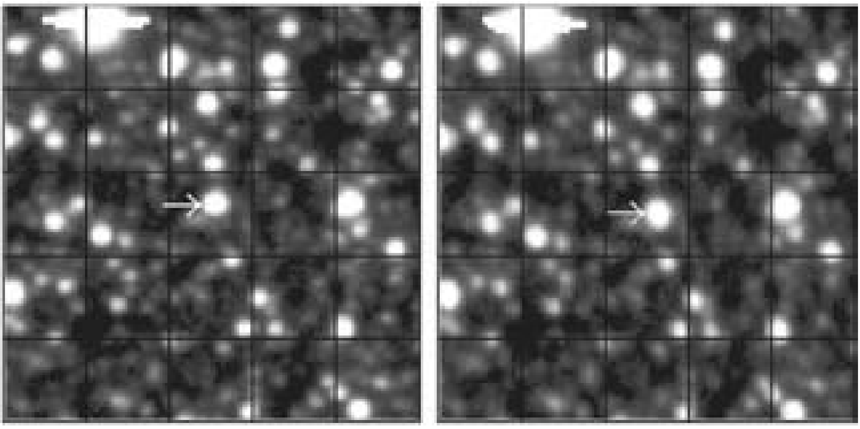

Figure 1.5. Some of the stars seen toward the center of the Milky Way are moving at very high velocities, perhaps tossed from young binary systems. Over 150 High Proper Motion (HPM) stars were detected during observations made for the Lawrence Livermore National Laboratory (LLNL) Massive Compact Halo Object (MaCHO) collaboration, a project that scans tens of millions of stars to look for *microlensing* events caused by foreground dark matter. These two images indicate the motion of an HPM star in our own galaxy (indicated in each frame by an arrow). The observations were made with the 1.3-m Great Melbourne Telescope at Mount Stromolo Observatory, Australia. Courtesy of Lawrence Livermore National Laboratory.

of civilizations in the galaxy. With optimistic values for such variables as the probability that complex life arises and the length of time that civilizations may be expected to last, one ends up with a galaxy full of civilizations. Based on recent findings about our galaxy and our solar system, Ward and Brownlee suggest that the Drake equation is wrong. Intelligent life in the galaxy? We might be it.

Ward and Brownlee's arguments range from what substances are required in a cloud of gas collapsing to form a star that could eventually form terrestrial planets with livable atmospheres to the varying temperature and *abundance* of important chemicals in the disk of our galaxy. The conclusion that they come to is that our situation here in the solar system may not only be unusual but possibly unique. The placement and relative circularity of the orbits of the planets, the type of star that we orbit, and our placement in the galaxy (not too close to the center with all of those stars; not too far out, where there aren't enough heavy elements) are all critical. If any of these factors had been different, Earth might be host to simple life (bacteria, etc.) but would likely have been hostile to the evolution of complex multicelled organisms that can build radio telescopes and look for other life forms.

David Darling, author of the recently published *Life Everywhere: The Maverick Science of Astrobiology*, takes a contrary view. Based on recent results in the discipline of astrobiology discussed later in this chapter, he finds evidence that some of the precursors to life might have actually begun to assemble in the incredibly harsh conditions of interstellar space. The resolution of these two disparate views will have to await the discovery of life in some environment other than the Earth. And until astronomers or astrobiologists find clear signs of life elsewhere, the proposal that we are alone will be viable.

Water in the Solar System

The possible presence and detection of the life-sustaining water molecule on surfaces other than the Earth is one of the most intriguing recent issues in astronomy. As a result, much of the exploration of the solar system in the 1990s concentrated on efforts to find evidence of the presence of water in the solar system, either currently or at some time in the past. Antoine Laurent Lavoisier (1743–1794) first determined the composition of this precious liquid in the eighteenth century: two parts hydrogen and one part oxygen. We tend to think of water as the substance that makes the Earth unique in our solar system. Our planet is an oasis of water-based life in the cold vacuum of space.

In terms of atmospheric water, that is correct. The other planets have little or no water in their atmospheres. However, imaging and spectroscopy of other solar system objects and even distant star-forming clouds have shown us recently that water is abundant throughout the solar system and even in the space between the stars. Some of the Jovian moons, in particular Europa, appear to show the presence of subsurface water. Where exactly have we detected the presence of water other than here on Earth?

Comets

Comets are made mostly of water ice, with up to 80 percent of their mass in water. When they come close to the sun in their highly elliptical orbits, they grow long tails of materials that are "boiled" off the surface of the comet. Much of what is spectrographically detected in these tails is the constituent parts of water, the hydroxyl (OH^-) and hydrogen (H^+) ions.

The Moon

Lunar seas were long imagined to exist on the surface of the moon. The Latin term for the moon's "seas," or *maria* (singular *mare*), grew out of this ancient belief. However, high-resolution telescopic images long ago showed that the "seas" are in fact ancient volcanic plains. Surprisingly, the Clementine mission to the moon in 1996 showed evidence that water was located at the moon's south pole. Later, the Lunar Prospector mission (in 1998) detected evidence for the presence of water at the moon's north and south poles, permanently in shadow. However, a planned crash of the Lunar Prospector mission at the south pole failed to send a detectable ice plume above the lunar surface. While the results of these missions are still debated, most astronomers agree that these results showed that water can survive in incredibly harsh environments for long periods of time, as long as it is shielded from direct exposure to solar radiation.

Mars

The recent imaging missions to Mars (in particular, the Mars Global Surveyor) show clear fossil evidence of flowing water (see previous section), and it has long been understood that the polar caps of Mars are at least partially composed of water ice (Figure 1.6). Unfortunately, one of the missions that would have explained much about the polar region, including its water content, was lost as it arrived at the planet. The surface pressure of Mars is far too low to allow water to exist in a

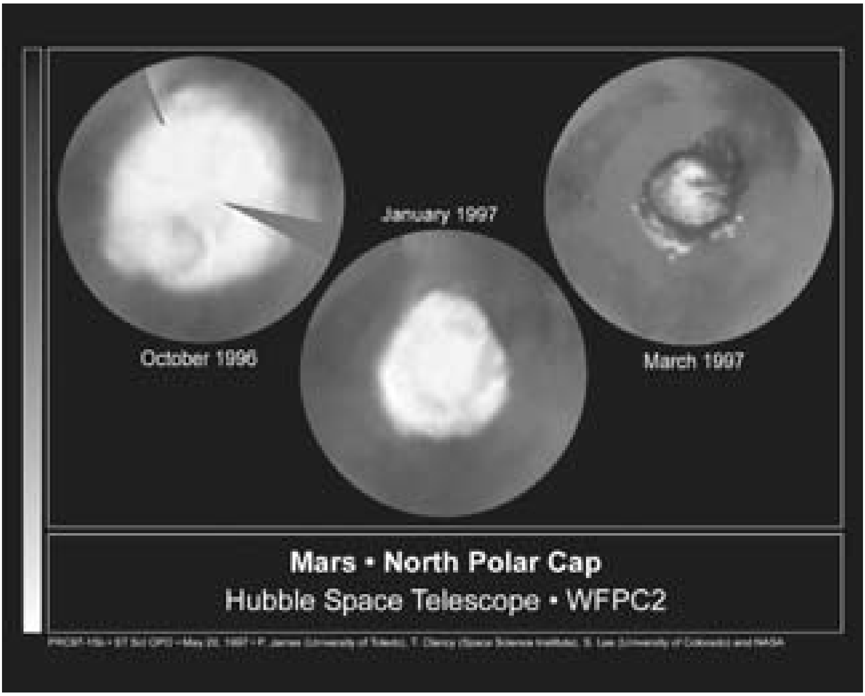

Figure 1.6. This series of images shows the changing polar ice cap of Mars as observed with the Hubble Space Telescope between October 1996 and March 1997. The size of the polar ice cap changes with the seasons, much like the polar ice caps on Earth. The ability to image planets outside our solar system with this level of detail is many decades in the future. STScI. Courtesy of NASA.

liquid state there now, but evidence for subsurface water both in the past as well as relatively recently is widespread.

In a controversial hypothesis made in the late 1980s and based on Viking Orbiter images, Jet Propulsion Laboratory (JPL) geologist Tim Parker proposed that one-third of the Martian surface may once have been covered by ocean. Widely discounted at the time, the proposal had another test recently when the topographical map provided by MOLA was published. While the “shoreline” of an older, larger sea varies too much to have been what Parker proposed, the smaller shoreline located inside the larger one is at least not disproved by the new MOLA data, which shows that the smaller shoreline varies little in elevation. This result suggests that, at one time, it could have been the location of a continuous “shore.” The 1989 work has been revisited with the collaboration of Lunar and Planetary Institute scientist Stephen Clifford, who thinks that the theory has merit.

In the spring of 2001, Paul Withers (University of Arizona) and Gregory Neumann (Massachusetts Institute of Technology) proposed that the northern hemisphere topography could just as easily be accounted for tectonically. While the presence of subsurface water on Mars is widely accepted, the explanation for the northern hemisphere topography is still up for grabs.

Europa (Moon of Jupiter)

The Galileo mission to Jupiter and its moons has provided stunning images of the surface of Europa, and its "cracked shell" appearance, implying the presence of a subsurface liquid layer. Gravitational stresses are sufficient to maintain water in its liquid state in the interior despite Europa's great distance from the warmth of the sun and its lack of an atmosphere.

The visual evidence was compelling—with high-resolution images showing raftlike chunks of ice that appear to have at some point cracked and separated in ways seen in Earth-bound Antarctic ice—and instruments sensitive to magnetic fields appear to have provided additional evidence, independent of visual observation. The instruments suggest the motions of electrically charged substances (perhaps saltwater) moving within 5 to 10 miles of the icy surface of the moon. NASA has begun plans for a dedicated Europa Orbiter and perhaps a surface landing within the coming decade.

The Interstellar Medium

Radio telescopes have detected the presence of water molecules in the large clouds of gas between the stars. Water masers are clouds of water molecules that have absorbed some energy from collisions or infrared radiation and that have not yet lost this energy as a result of energy transitions. The water masers subsequently amplify background electromagnetic radiation in exactly the way that lasers in Earth-based laboratories do. Such water masers have been detected in the environments of young and old stars, a fact that implies the presence of large amounts of water in the environments around many stars. This water ice may play an important role in the advent of life in newly formed planetary systems. And some of this water eventually may be locked up in the far reaches of other systems (their Kuiper Belts and Oort Clouds), providing billions of years of comet infall. The nascent field of astrobiology is beginning to study the possibilities that comets may indeed rain down the building blocks of life onto newborn planets.

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ASTROBIOLOGY

Astrobiology is a very young discipline and one that has grown dramatically in the past few years. In April 2000, the first astrobiology science conference was held at Ames Research Center. In 1999, the first graduate program in astrobiology opened its doors at the University of Washington. Other major research universities, including Stanford, Tulane, and the University of Colorado, offer courses and concentrations to graduate students in astrobiology. NASA held a second astrobiology conference in April 2002. NASA itself has taken on the task of laying out a plan for the development of the field in a document called *The Astrobiology Roadmap* (see Chapter 4 for selections from this document). The Roadmap began as a workshop sponsored by NASA in 1998 and has developed from there. The roadmap recommends that the field address three broad questions: (1) How does life begin and develop? (2) Does life exist elsewhere in the universe? (3) What is the future of life on earth?

The study of phenomena at the interface between astronomy and biology—considered for at least the last 50 years—has been variously called *exobiology*, *bioastronomy*, and *astrobiology*. The latter term is gaining an increasingly firm foothold. As experts in the fields of astronomy, biology, and geology have begun to talk and collaborate, the rate of discovery has been dizzying. As has been pointed out in many of the recently published popular books on the topic, the rash of collaboration and publication has not necessarily produced agreement but rather an array of sometimes contradictory, testable hypotheses about the origin of life on the Earth, the possible propagation of life in the solar system, and the prospects for life in the universe at large.

Mars Meteorite

In perhaps the best-known astrobiology story of the past decade, a NASA-Stanford research team claimed in August 1996 that a Martian meteorite (ALH84001) showed evidence of fossilized bacteria. The evidence included the presence of carbonate globules and, within the globules, iron oxides and sulfides often associated with earthly bacteria. Researchers also detected PAHs (polycyclic aromatic hydrocarbons) within the sample and even imaged regions of the meteorite that contain structures bearing a striking similarity to earthly fossilized bacteria. The big difference here is that the fossilized Martian bacteria (if that is what they are) are much smaller than any bacteria known to exist on the Earth.

These claims have been widely challenged since they were first made, and a number of independent investigations point to earthly contamination as an explanation, for example, of the presence of the PAHs. Other studies suggest that the carbonate globules could have formed in a hot, dry environment, not the ocean the original paper claimed as the origin. And in the spring of 2001, several new studies were published contending that the presence and purity of magnetite in

ALH84001 provides solid evidence of biological activity. The investigation of this meteorite has pointed out the difficulty of "proving" that life existed on early Mars. Unless the criteria for proof are clear and agreed upon before discovery of a test object, the waters become increasingly muddy. Uncontested fossil evidence (or lack thereof) of bacterial life on Mars will likely have to await robotic or human fossil hunting on the planet itself.

Containers in the Interstellar Medium?

The famous Miller-Urey experiments in the 1950s showed that when a chemical broth of the simple molecules that were present on the early Earth were zapped at room temperature and atmospheric density with large electrical currents (simulating lightning), more complex organic molecules were readily formed. These experiments laid the basis for the "primordial soup" theory of the origin of life on Earth. Based on these simple but inventive tests, the idea that the Earth's surface was where "prebiological" processes began seemed plausible.

In the early part of 2001, an even more dramatic discovery was made. Researchers at NASA Ames Research Center and the University of California at Santa Cruz found that, by placing molecules found commonly in interstellar space in conditions that replicate those as harsh as those in the interstellar medium (ISM), they were able to form structures similar to cell walls. If *prebiotic* structures are able to form in the interstellar medium—the places between the stars—then the prospects for life in the universe might be even more promising than astronomers and biologists had thought.

The experiment took place in a vacuum held at 15 K and started with only water, methanol, ammonia, and carbon monoxide, all molecules that, for more than a decade, have been commonly observed to exist in the ISM, using millimeter-wave radio interferometers like the Owens Valley Radio Observatory (OVRO) Millimeter Array and the Berkeley Illinois Maryland Association (BIMA) Array. The temperature of the chamber was cycled to room temperature and back to 15 K over a period of a month and a half, while being bombarded with ultraviolet radiation, the kind of radiation found in the near environments of stars. The resulting "goo" consisted of a variety of complex molecules and, perhaps most surprising, small spherical blobs resembling cell walls made of fatty acids (lipids).

What some find most exciting about this research is that nonbiological processes (chemical processes common in the environments of young stars) might be able to form one of the essential precursors of biological life, a "container" in which nonequilibrium conditions can be maintained. If such containers could survive an impact with the Earth (and computer simulations suggest that, for a comet, surviving a "glancing" impact is indeed possible), then life might have a big head start on a young planet.

Conditions on Early Earth: Ripe for Extremophiles?

At one time the prevalent view was that the early Earth was a warm, wet place and that its surface was ripe for the advent of life in sun-drenched surface pools. The view of the early Earth has been rapidly changing, however. Models of planetary system formation now show us that the very young Earth would have had most or all of its volatiles (including water) vaporized by the young, hot sun and that a collision early in its life with a Mars-sized protoplanet probably revaporized material on its surface and created the moon.

Even after the cataclysmic event that is likely to have formed the moon occurred, the surface of the Earth was bombarded—probably for some hundreds of millions of years—by shrapnel from the early solar system, making its surface hostile to life. And yet the fossil record indicates that simple life got a foothold on the Earth at very early times, with fossil evidence of bacteria going back some 3.8 billion years. Whatever early life thrived on the Earth, it appears to have been able to weather the impacts and resulting temperatures of a very turbulent young solar system.

Scientists are beginning to compare this astronomical evidence to biological evidence that all life on Earth might have a common ancestor in what are called *hyperthermophiles*, simple organisms that can survive very high temperatures. There are at least two ways to interpret this common ancestry: Either the earliest life took hold near thermal vents in the Earth's early oceans, or only those bacteria that could weather high temperatures survived the Earth's young environment. In any event, astrobiologists are now much more open to the idea that life may originate not at the surface of a planet but deep inside it and that looking for signs of simple life, if it is hidden deep within its host planet, might be very difficult. Life on Earth may not have originated in sun-drenched muddy pools after all—but in the deep, hot reaches of the Earth's early oceans.

SETI

SETI (Search for Extraterrestrial Intelligence) gained a lot of visibility in the 1990s with the release of the movie *Contact*, starring Jodie

Foster and based on the Carl Sagan novel of the same name. The SETI effort is not new and is founded on the assumption that since the conditions that give rise to life appear to be widespread, and the universe is very old, the universe is most likely filled with intelligent life.

Incorporated in 1984, the SETI Institute describes its purpose this way:

> [T]o conduct scientific research and educational projects relevant to the nature, prevalence, and distribution of life in the universe. This work includes two primary research areas: 1) SETI, and 2) Life in the Universe. Concurrent with its research focus, the Institute strives to contribute to both formal and informal science education related to these fields of interest.

Funded by federal dollars until 1994, the institute now relies on private donations. Most recently, Paul Allen and Nathan Myhrvold of Microsoft committed $12.5 million in support of a dedicated SETI instrument. Since its inception, and until this time, SETI has depended on shared use of various arrays and telescopes. The Allen Telescope Array (ATA), which is now in its design phase, will significantly increase the reach of the SETI effort, allowing SETI scientists to search a larger portion of our galaxy for radio signals, starting in 2005.

The goal of the SETI search is to find a clear signal of extraterrestrial, intelligent origin. For many reasons, the thought is that such signals would be transmitted in a relatively quiet portion of the radio spectrum, where the Milky Way galaxy is the least “noisy.” One argument is that the 21-cm line of neutral hydrogen (the most abundant element in the universe) would be a likely wavelength to transmit, not only since it falls in this quiet part of the spectrum but because transmitting at its wavelength would also indicate knowledge of the fundamental nature of hydrogen in the universe.

The SETI effort is in many ways a complementary effort to the search for extrasolar planetary systems. One search takes the philosophy of searching for habitable planets. The other proposes to look for the communications other intelligent life forms might broadcast. Both searches are technically challenging and catch the imagination of the public. The search for planets has (as we have seen) already been successful. The SETI program has yet to detect an intelligent signal of extraterrestrial origin. In the meantime, these two searches push the technological limits of spectroscopy and high-speed electronics in an effort to see whether we humans have any company in space.

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GALAXIES

Stars are collected together into gigantic groupings we call galaxies. In the early part of the twentieth century, a debate raged as to whether the objects that had been identified by William Herschel (1738–1822), Charles Messier (1730–1817), and others, the so-called spiral nebulae, were nearby (and hence relatively small) or at great distances (and enormous). As it turns out, most of the spiral nebulae that had been detected at the time were in fact what we now call *spiral galaxies*, collections of hundreds of billions of stars into flattened structures with density waves that sweep around their disks, triggering cycles of star formation. As cells are the building blocks of our bodies, so stars are the building blocks of galaxies. Elliptical galaxies consist mostly—if not exclusively—of stars, while spiral and irregular galaxies consist of mixtures of stars, gas, and dust. As it turns out, stars do not account for most of the mass of a galaxy. Viewed on sufficiently large scales, it becomes apparent that another contributor "outweighs" the stars. Currently, this material is called *dark matter*, since astronomers are not at all sure as to what it might be. Does dark matter consist of massive neutrinos, brown dwarf stars, planets tossed out of protoplanetary systems, MaCHOs (Massive Compact Halo Objects), or WIMPs (Weakly Interacting Massive Particles)? There is no agreement as to which of the currently proposed answers (if any) is correct. In the sections that follow, we survey some important recent discoveries concerning the nature of stars and galaxies.

The Nature of Solar Neutrinos

One of the most intractable problems in astronomy, and indeed a topic included in Chapter 6 of an early draft of this manuscript, was the nature of solar neutrinos. Astronomers have a fairly hearty theory for the way in which stars generate their enormous energy. Early ideas that the sun shone by chemical burning or gravitational contractions fell short by a factor of thousands or millions in the amount of time that they predicted the sun would shine. Once it became clear from the geological record that the sun had been shining for over 4 billion years, it was clear that the source of energy in the sun had to be something that had not yet been proposed. As it turns out, *nuclear fusion* is the way in which the sun produces its prodigious energy. In brief, the temperatures at the center of the sun are so high, and the pressures so great, that hydrogen nuclei (protons) are fused together to make helium nuclei. In the process of generating helium, the core of the sun generates particles called *neutrinos* that interact with other matter so weakly that they come streaming out of the sun's core, getting here far in advance of the photons that can take 100,000 years to escape that dense environment.

The vexing problem, for many years, was that these reactions led to a predicted "solar neutrino flux," or the number of neutrinos that a detector here on the Earth should catch every second. Try as they might, neutrino physicists and astronomers did not detect the number of neutrinos that the theory predicted, typically detecting about one-third of the expected number. This disagreement could have had one of several causes: (1) the model of nuclear fusion in the sun's core was incorrect, (2) the detectors were flawed, or (3) our theory of solar neutrinos was incorrect.

Most scientists were working on the third of these possibilities, and it turns out that developments in the theory of *neutrino oscillation*, paired with a detector that could catch all three types of neutrinos solved the problem. Physicists had for years proposed that if the neutrinos changed character while they traveled from the sun to the Earth, some of them might be undetectable by the time they reached the Earth. In the most recent result the Sudbury Neutrino Observatory (SNO) in Ontario, Canada, has indeed detected the proper flux of neutrinos as predicted by neutrino theory. It accomplished this feat by being sensitive not only to electron neutrinos (as were all the other neutrino detectors) but also to tau and mu neutrinos. This result provides strong evidence not only that we understand the nuclear fusion occurring at the sun's core but that neutrinos do indeed "oscillate" between families (electron, tau, and mu) as they make their journey from the sun. While the solar neutrino problem, as it was dubbed, may have been solved, particle physicists must now attack the problem of neutrino oscillation.

Probing the Milky Way Galaxy with X-Rays

For most of the history of astronomical observation, astronomers have had detectors sensitive only in the visible part of the electromagnetic spectrum. From before recorded history to the time of Galileo (1564–1642), the only available detector was the human eye. Having evolved on a planet illuminated by a sun that puts out most of its energy in the yellow/green part of the visible spectrum, the human eye is an ideal detector for very bright or nearby stars and for objects that glow in reflected starlight. The sun, moon, planets, and other stars are easily visible in this part of the electromagnetic spectrum. But by the nineteenth and twentieth centuries, scientists realized that the visible part of the spectrum is only a tiny fraction of the whole.

Wilhelm Conrad Röentgen (1845–1923) is credited with the discovery of X-rays in 1895 while using a Crooks tube, a glass vacuum tube with positive and negative electrodes. Roentgen received the Nobel Prize in 1901 for this important discovery. While the medical uses of X-rays were immediately apparent, it would be nearly a century before high-resolution X-ray images of astronomical objects were possible. In fact, it took nearly as long to realize that astronomical objects even emitted X-rays. By the 1980s and 1990s, astronomers were getting their first views of the X-ray sky from the orbiting Einstein and Röentgen (ROSAT [Röntgensatellit]) satellites.

Described in more detail in the following chapter, the Chandra X-Ray Observatory was launched into Earth orbit in 1999, and some of the first images it has obtained have been stunning. The Crab Nebula (a known source of strong X-ray emission) was one of the first sources imaged. Figure 1.7 shows the object, the result of a supernova explosion that was first observed in 1054 CE as it looks at optical and X-ray frequencies. Telescopes like Chandra have given astronomers, for the first time, high-resolution views of the energetic processes associated with X-ray emission.

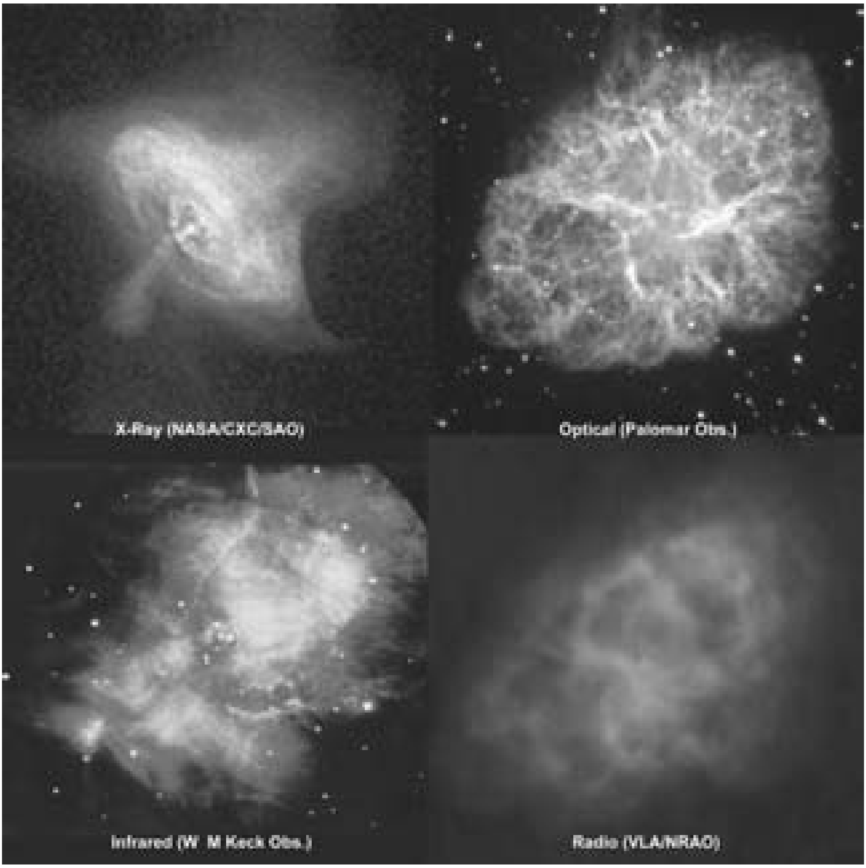

Figure 1.7. The universe at different wavelengths. For the first time in history, we are able to see objects like the supernova remnant known as the Crab Nebula at the same resolution across many wavelengths. The images above show the nebula (clockwise from *top left*) at X-ray, optical, radio, and infrared wavelengths. The images are to the same scale, but, for example, the high-energy X-ray photons are distributed in a very different manner than the lower-energy optical photons. Courtesy of NASA and the Smithsonian Astrophysical Observatory.

Magnetic Fields in the Galaxy

The Crab Nebula is a prime example of the importance of understanding magnetic fields in astronomy. Near the nebula, electrons are thought to spiral around magnetic field lines, giving off energy through a process called synchrotron radiation (see Chapter 2), which requires accelerating charged particles to produce radiation from the radio (low-energy) to the gamma ray (high-energy) part of the spectrum. The Chandra image shown in Figure 1.7 shows us the location of the highest-energy photons that we can detect from this source with high resolution.

Magnetic fields have a number of interesting and detectable features. They polarize light that passes through them, they “split” electron energy levels into substates, and they accelerate charged particles in such a way as to produce “synchrotron” radiation. All of these effects can be used to detect the presence and measure the strength of magnetic fields in distant objects. The realization that magnetic fields are everywhere has led to their careful incorporation into theories of how astronomical objects evolve.

Giles Novak (Northwestern University) and collaborators have been investigating the nature of the magnetic fields at the center of the Milky Way galaxy, the home of hundreds of billions of stars, including the sun. The center of our own galaxy is both near and far, observationally speaking. While there are no galactic centers that are closer, we also have the distinct disadvantage of looking at our galaxy’s center through the gas and dust that is found interspersed among the stars. In fact, at optical wavelengths, we actually have a better view of the centers of much more distant galaxies than we do of the center of our own.

However, at radio wavelengths, astronomers are able to explore not only the material at the galactic center but also the magnetic fields there. These magnetic fields may be detected in several ways. One method is to look at the polarization axis of polarized light. Magnetic fields polarize light, and Novak and his collaborators have used the SPARO (Submillimeter Polarimeter for Antarctic Remote Observing) 450-micron imager to make wide-field images of the magnetic field near the galactic center. The results are preliminary, but they suggest that the polarization is perpendicular to the galactic plane, and the magnetic field is parallel to the plane. The nature and orientation of the magnetic field at the center of the galaxy will give us insight into the object that might be at the very center: a black hole. Observations such as these are being made in an effort to understand what is happening at the center of our own very typical galaxy, in the hope of understanding the Milky Way itself as well as other galaxies like it.

A Black Hole in the Milky Way

Black holes are a favorite subject of science fiction novels and movies. They have been proposed to be portals to other universes, wormholes that allow people to hop around the universe at speeds greater than light. Sometimes it is important to remember that, for all their science fiction appeal, the existence of black holes is, on the one hand, quite well established, yet their known properties are far stranger than any imagined by Hollywood.

One can imagine black holes coming in two sizes, normal and extremely huge. The normal variety of black hole is sometimes called a *stellar-mass* black hole; it results from the collapse of a massive star. As massive stars evolve and burn through their nuclear fuel, fusing ever-heavier elements, they eventually “hit a wall” when they reach the element iron. At this point, the core of the star (which, by virtue of the energy produced in fusion, has been supported against gravitational collapse) shuts down, and the overlying layers begin to collapse.

The collapse ends when material “bounces” from the incompressible core and propagates out into space as a *Type II supernova*. If the star is not too massive, the core will be supported by neutrons that are incompressible, yielding a neutron star. However, if the star is sufficiently massive ($M > 3$ solar masses), *neutron degeneracy pressure* will be insufficient to halt the collapse, which therefore continues without stopping. The collapse of the star proceeds with no force to oppose it, and a stellar-mass black hole is therefore born. Since supernovae occur too infrequently and (fortunately for us) too distant to observe in real time, astronomers must do computational work on these collapsing stars, writing computer programs that simulate the physical processes that ensue. Later in this chapter we give a few examples of this type of work.

Why are these objects called black holes? Because their mass is concentrated in a sufficiently small volume that even light cannot escape from within a certain radius around them. Since no information escapes in the form of light, the portion of the universe enclosed in that radius is “black.” Larger black holes may result from the coalescence of matter in a small radius at the centers of galaxies. Recent observational results in the field of *active galaxies* suggest that many galaxies have supermassive black holes at their centers, even if the nuclei are only occasionally active.

Our own Milky Way may well have a supermassive black hole at its center. Astronomers can explore this possibility by looking at the orbits of stars and gas near the center of the galaxy. These observations can be difficult because the material in the disk of the galaxy, which lies between the galactic center and us, absorbs visible light. If, then, we want to see the stars and gas near the galactic center, we have to look at other wavelengths, namely, radio and infrared. In the infrared, astronomers can track the orbits of stars, and in the radio, they can track the motions of the gas.

Using the fact that the rotational velocity at a particular radius tells us about the mass enclosed within that radius, we can determine the mass within the central regions of the galaxy. The results have been compelling. In 1998, UCLA (University of California at Los Angeles) astronomer Andrea Ghez reported that a black hole with a mass of more than 2 million times that of the sun is at the center of our Milky Way galaxy. The results were based on Ghez's observations with the 10-m Keck I Telescope at Mauna Kea, Hawaii. She made infrared "speckle" observations of over 200 stars near the galactic center. Speckle techniques are widely used by astronomers to improve the resolution of their observations. According to Ghez, "The atmosphere blurs your vision, but speckle interferometry clears the picture up; it's like putting on glasses. Think of seeing a coin that looks distorted at the bottom of a pond. We take thousands of freeze frames, and then can determine what is distorted and what is really at the bottom of the pond."

The motions of stars near the center of our galaxy show that there are 2.6 million solar masses of material located within a very small radius, which, in turn, implies that the region contains a supermassive black hole. While the stars appear to be orbiting a source nearly 3 million times as massive as the sun, they are located in an area only about 100 times the size of the solar system.

In addition, an independent project (based at the Center for Astrophysics, or CfA) has used the Very Long Baseline Array (VLBA) to determine that the radio source associated with the galactic center (called Sagittarius A*, or Sgr A*) has, over a long monitoring period, moved very slowly. Team leader Mark Reid and his collaborators have concluded that because Sgr A* moves so slowly, the detected movement is consistent with Sgr A* being a black hole. The derived mass was about 3 million solar masses, a figure in rough agreement with the stellar data.

Gravitational Glasses

Albert Einstein is probably best known for his equation $E = mc^2$, the formula that stated the equivalence of mass and energy and that, for the first time, made it possible to explain the sun's prodigious rate of energy generation. The sun's brightness did not derive from chemical burning, or gravitational contraction, but apparently from the conversion of a small amount of its mass into a large amount of energy—the gain being at the rate of the square of the *speed of light, 300,000,000 meters per second*: a very large number indeed.

While this may be Einstein's most famous contribution at the level of popular culture, it represents only a small portion of his total contribution to our understanding of time, matter, and space. Einstein's general theory of relativity predicts that gravitational fields—which, since the time of Isaac Newton (1642–1727), had been known to act on matter—might well act on photons of light as well. Einstein's prediction was unusual, since the Newtonian conception of gravity was as a force acting between any two objects with mass. However, photons are massless, so there should be no gravitational effect. But as Einstein saw it, gravity is not a force between two objects with mass but a distortion in the fabric of the universe that results from the presence of mass. This distortion should affect the paths of other masses, as well as those of massless entities, such as photons. To test this theory, Einstein proposed that a solar eclipse (occurring on May 29, 1919) be used to measure the displacement (if any) of the position of a star near the sun. The idea was that any displacement of the star from its known position would be the result of the sun's mass causing the photons of light to change from a straight-line trajectory as they passed very near to the limb of the sun. The experiment was carried out, and the resulting displacement was in agreement with the predictions.

Once this effect was established, it was realized that foreground galaxies and clusters of galaxies—objects of incredibly great mass—could very well be used as "lenses" to view the distorted images of more distant objects. Depending on the relative positions of the foreground galaxy and the background source, the "lensed" object might look like a doubly peaked source, an arc of emission, or, if the two were perfectly aligned and symmetrical, a ring.

The Hubble Space Telescope, the Very Large Array, and the Very Long Baseline Array (see Chapter 2) have all produced a number of such images (Figure 1.8). The shape of the lensed objects can be used to determine the amount of mass in the lensing source, and ray-tracing

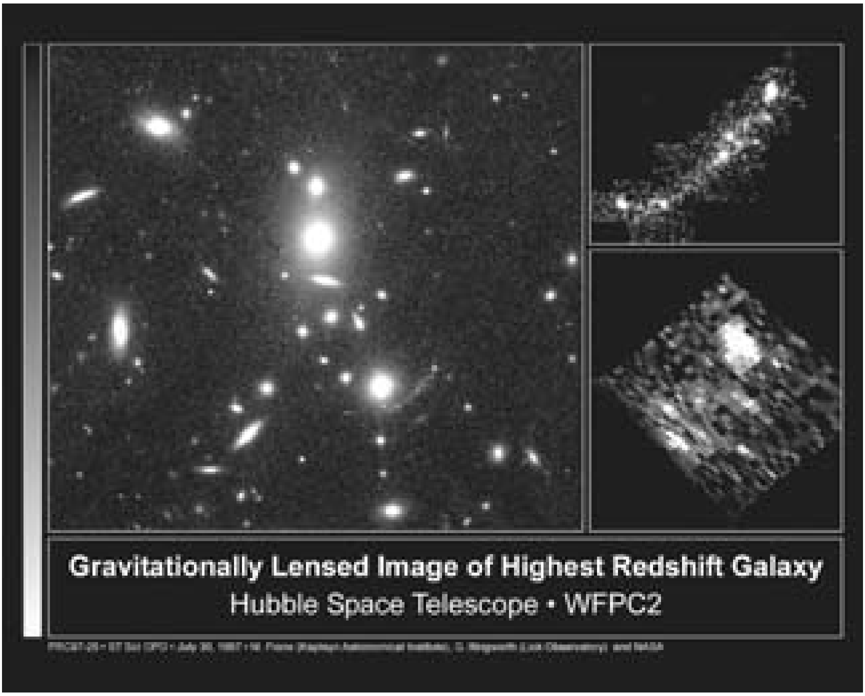

Figure 1.8. This Hubble Space Telescope (HST) image of the galaxy cluster CL1358 + 62, released in 1997, showed the remarkable ability of gravitational lenses to give us a clearer view of even more distant galaxies. A gravitational lens (like a conventional lens) brightens and magnifies the distant source, apparently filled with knots of star-forming activity. At the time of discovery, the lensed galaxy was the most distant ever observed. The detailed images to the *right* show the lensed background galaxy as imaged (*upper*) and as it appears when the distorting effects of the gravitational lens are removed (*lower*). Courtesy of Marijn Franx (University of Groningen, The Netherlands), Garth Illingworth (University of California, Santa Cruz), and NASA.

algorithms can even be used to determine the exact distances to the lensing sources.

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COSMOLOGY

Every culture has a creation myth. The first words of the Old Testament describe the creation of the universe and everything within it over a span of just six days. For most of history, the origin of the universe has been the exclusive domain of philosophers and priests, because the observational and theoretical framework required to explain the early universe scientifically was not in place until the twentieth century. Only in the last century has a vigorous debate about the origin of the universe moved from purely philosophical and religious circles into discussions that involve science and telescopic observation. Scientists are clearly newcomers to this discussion, but they have made great contributions.

The first observational evidence that the universe was in fact changing came from the theoretical work of Albert Einstein, who was able to show that, in either a finite or infinite universe, static solutions to his general relativity equations were not possible unless one added to them the so-called cosmological constant. As long as the density and pressure of the universe were nonzero, Einstein’s work seemed to show that there are no static solutions—that is, the universe had to be changing. To arrive at a static universe, then, Einstein modified his equations so that static solutions were possible. However, a major observational discovery followed rapidly on the heels of his theoretical work. In

1922, Alexander Friedmann came up with solutions to the equations that Einstein had proposed that describe what we now commonly know as the different "geometries" of the universe. Depending on the amount of matter in the universe (the density of matter), the universe will have geometries that can be described as *closed*, *flat*, or *open*.

By 1929, Edwin Hubble had presented clear evidence that galaxies were all racing away from the Milky Way at velocities proportional to their distances. That is, the universe was expanding and was not static. In fact, the simplest form of Einstein's equations, which had predicted a dynamic, changing universe, now appeared to be correct after all. With clear evidence that everything in the universe had been at one place (a "singularity") at some time in the past, theoretical physicists and observers began to explore the implications.

Recent work by two groups that gauge distances to galaxies from the brightness of supernovae that occur in them suggests that there is not enough mass in the universe to hold it together. Not only that, but the universe appears to have been expanding more slowly in the past than it is now, implying that a repulsive force akin to gravity may be pushing the universe apart.

A Runaway Universe?

Common understanding—even a few years ago—was that while the universe was certainly expanding, its expansion was gradually slowing. As a result, it was believed that the expansion would either slow to a crawl or actually stop, so that the universe would ultimately collapse in what some astronomers dubbed a *Big Crunch.* (For a fanciful description of this "end time," see Kurt Vonnegut's science fiction novel *Timequake* [1997].) Many, both in the astronomical community and the general public, were surprised in 1998 when two teams independently announced that they had detected something altogether different: Far from slowing, the expansion of the universe appears to be accelerating. Not only were galaxies moving apart; they were moving apart more rapidly with the passage of time.

How had astronomers determined this surprising result? They used a certain type of explosion (called a Type Ia supernova) as a standard light source in the universe and then studied the detected brightness of these explosions to determine the distance to the host galaxies (Figure 1.9). Type Ia supernova occur when a *white dwarf* star accretes enough material from a companion to collapse and explode. Astronomers are always looking for things that are (anachronistically enough)

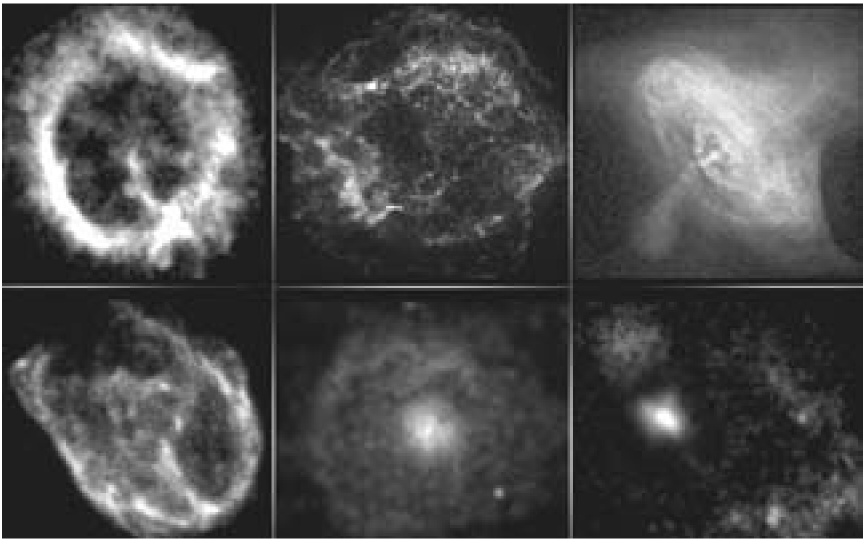

Figure 1.9. Extragalactic supernova searches typically blink between images made at different epochs to see if "new" sources have appeared in a galaxy in the intervening time. Closer to home, the Chandra X-Ray Observatory has made many supernova remnants in our Milky Way galaxy visible in a new way. These images show details of the distribution of high-energy photons in six galactic supernova remnants. They are, clockwise from *top left*: E0102–72.3, Cassiopeia A, Crab Nebula, PSR 0540–69, G21.5–0.9, and N132D. Courtesy of NASA and the Smithsonian Astrophysical Observatory.

called *standard candles*—objects that have a very well-determined "intrinsic" brightness. If astronomers know how bright an object *really* is and how bright it *appears* to be, then they can determine how far away the object is, since the brightness of any object is known to decrease as distance squared. For example, a 100-watt light bulb at a 2-m distance is four times as faint as the same 100-watt light bulb at a 1-m distance. If astronomers want to see objects that are very distant, they must find standard candles that are intrinsically very bright and thus still detectable even hundreds of millions of light years away. Which brings us back to the Type Ia supernovae. These events are exceedingly energetic, and they are visible at very great distances. Why are large distances important? Because the farther away we look, the farther back into the history of the universe we also look, and when we look back in time, we are able to compare the expansion rate of the universe then and now and see if the rate has been constant.

One research team at Lawrence Berkeley Labs, headed by Saul Perlmutter, perfected a reliable approach to finding the relatively rare Type Ia supernovae. The Perlmutter team observes between 50 and 100 fields, each containing about 1,000 galaxies. They return to the same fields three weeks later and reimage them. A comparison is made between the images. Supernovae show up clearly as bright spots, and follow-up spectra of these supernovae pinpoint exactly when the supernova exploded and its specific "type." Astronomers use a graph called a *light curve* to show the temporal evolution of the supernova explosion. This figure plots the brightness of the supernova over time and shows where in the evolution of the explosion the observations were made. With this information, the team can go from a detected brightness to a distance, since the way in which the brightness of these sources changes with time is well known. The significant question that these observations have raised is: What force or effect is causing the expansion of the universe to accelerate?

In formulating general relativity, Einstein grappled with the particularly intransigent problem posed by the fact that, unopposed, gravity would cause the universe to collapse, while, at the time (in 1917), astronomers believed the universe was "stable," neither expanding nor contracting. To keep the universe from collapsing—in his model, that is—Einstein proposed a *cosmological constant* term. When Einstein learned shortly thereafter that the universe was indeed observed to be expanding, he concluded that the constant he introduced had been unnecessary, and he dismissed it as his "greatest blunder." However, the cosmological constant has now been resurrected to explain the detected acceleration in the expansion of the universe. For this term acts in the opposite direction from gravity, pushing things apart with a force that increases with distance and that, therefore, should cause any existing expansion to accelerate. Astronomers have dubbed this energy "dark energy," akin to "dark matter." These forms of energy and matter are "dark" in the sense that astronomers know that they are present because of their effects but do not yet know much about their detailed composition or nature.

The Geometry of the Universe

On April 26, 2000, an international collaboration of astronomers released one of the most widely anticipated astronomical results of the decade: high-resolution images of the *cosmic microwave background* (CMB) in a small area of the sky. The CMB is the afterglow of a time

12 to 15 billion years ago when the universe was much hotter, denser, and smaller than it is today. The photons we see as the CMB have been "stretched" by the expansion of the universe to the point that they are now detected in the long-wavelength (microwave) part of the electromagnetic spectrum. Early investigations seemed to show that the photons were distributed in a very smooth fashion across the sky. The question soon arose, however, that if the CMB were absolutely smooth, then how did the current "roughness" of the universe ever arise? That is, how would galaxies and clusters of galaxies ever form if the early universe were perfectly uniform?

Predicted by theorists in the 1940s and first observed (by accident—see Chapter 3) in the 1960s, the CMB was first seen to have variations as a result of the "all sky" low-resolution image produced by NASA's Cosmic Background Explorer (COBE) satellite in 1991. The COBE image showed that at very low levels the CMB was not smooth. There were fluctuations in the temperature of the CMB indicating that, even at very early times in the universe, there was, in some sense, structure. The COBE result did not have sufficient resolution (sensitivity to spatial detail) to explore the scale of these fluctuations, but it was clear that the scale of the fluctuations was smaller than the finest detail that COBE could detect. So the BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) mission took as its primary goal the detection of the scale of the temperature fluctuations in the CMB. The first results announced in 2000 made it clear that the mission achieved this goal. Through the use of a highly sensitive *bolometer* (a temperature-sensitive electronic device—see Chapter 2), the BOOMERANG mission has detected structures with scales of about 1 degree on the sky. For comparison, the moon has an angular size of about half a degree on the sky. So the dominant angular size of the fluctuations seen in the BOOMERANG result is about twice the size of the full moon's.

Unlike the COBE mission, which sought complete sky coverage at low resolution, the BOOMERANG mission has imaged about 3 percent of the sky with much higher resolution. An upcoming probe, the Microwave Anisotropy Probe (MAP) will make an all-sky image at BOOMERANG-level resolution.

Theorists have predicted that the size scale of the fluctuations in the CMB tells us about the geometry of space. In a *flat universe* (one in which parallel lines remain parallel forever), the fluctuations should have scale sizes of about 1 degree. An *open universe* (in which parallel light rays would eventually diverge) would have a smaller fluctuation scale, and a *closed universe* (in which parallel light rays would eventually cross) would have a larger scale. The BOOMERANG results appear to support a flat universe. Other lines of independent research from both the theoretical and observational side have also supported a flat universe (Figure 1.10).

The BOOMERANG results are also consistent with the Type Ia supernova experiments explained above, which appear to show that the universe is not only expanding but also accelerating in its expansion. The overlap of these two results implies that the universe came into being in a Big Bang, that it experienced a period of rapid growth (called inflation), and that the expansion of the universe will continue forever.

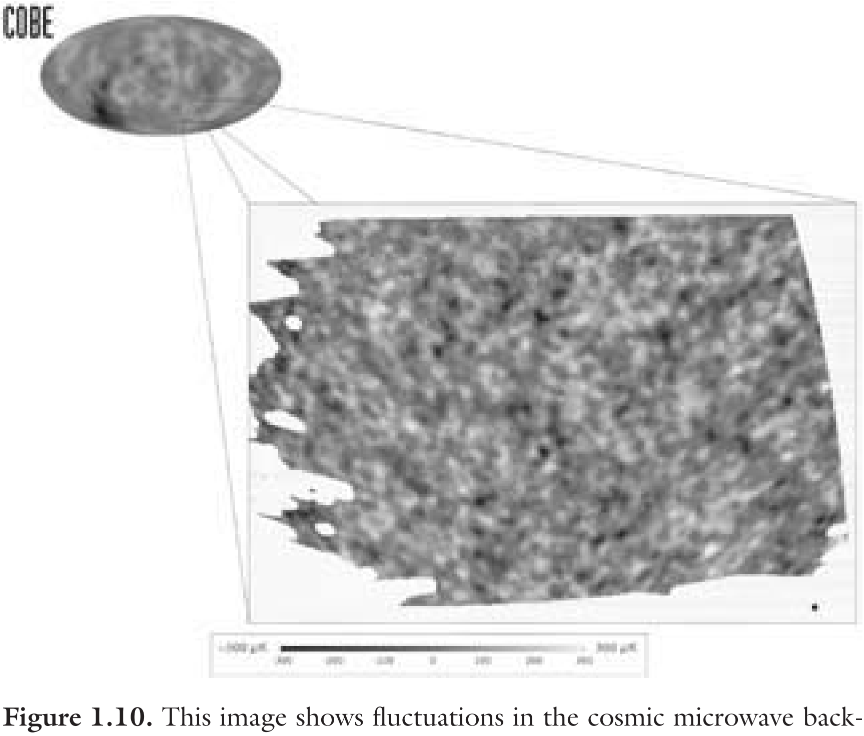

Figure 1.10. This image shows fluctuations in the cosmic microwave background (CMB) as imaged with the Cosmic Background Explorer (COBE), with the more recent results from BOOMERANG shown as a magnification of a small region in the *lower right* corner of the COBE image. The magnitude of the temperature fluctuations is indicated in the scale at the bottom of the image. The angular scale of the detected fluctuations (approximately 1 degree) is consistent with a flat universe. Courtesy of NASA, National Science Foundation and BOOMERANG.

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COMPUTATIONAL ASTROPHYSICS

Computation is hardly something new to astronomy. Over the millennia, astronomers and mathematicians have come up with ingenious devices that allowed them to extrapolate from known data the future positions of the planets with respect to the stars. Astronomers provided tables that were used by ship’s captains to navigate the world’s oceans in days long before Global Positioning Satellite (GPS) systems. And once Sir Isaac Newton proposed that the same laws of physics that cause the apple to drop cause the moon to orbit, astronomers, physicists, and mathematicians began busily calculating the motions of objects in the solar system and their effects upon one another. Once astronomers began to apply the laws of physics to astronomical bodies, many old questions were answered and new questions posed. If the planets orbit the sun, what keeps them in their orbits? Gravity, said Newton. What sort of orbital paths will result from a central force? Elliptical orbits.

In Newton’s time, and in all ages until the fairly recent past, the computations of astronomers were carried out with pencil (or quill) and paper, with early mechanical “calculating machines,” and then about the time of World War II, with computational machines that predated the first computers. The postwar invention of the transistor began a revolution that has resulted in incredibly powerful computers sitting on the desktops of a huge number of people in this country. The abilities of these computers now outstrip most of the uses that average consumers have come up with so far. But one application that still stretches even today’s best computers is computational modeling of systems of interest to astronomy and astrophysics.

Early computational work involved having computers carry out calculations of the forces between objects using Newtonian mechanics. In one example, astronomers might model two galaxies as consisting of thousands of point masses, each one representing hundreds of thousands of stars. The computer is given the rules (including the law of universal gravitation, or the force that exists between any two objects with mass) and calculates moment by moment how each one of those points pulls on every other point. After many hours (or hundreds of hours) of computer time, the astronomer has a "movie" that shows the distortion and disruption of the galaxies due to gravitational forces as they sweep past one another. This example is very simplified, but it demonstrates the great power of computational astrophysics: As long as all of the rules are included—and these rules are the fundamental laws of physics as we understand them, a growing list—astronomers are able to watch the evolution of systems that they would never have the hope of observing in real time. Important computational work has been carried out on galaxy mergers and collisions, the interior structure and evolution of stars, and some of the most energetic events in the universe, the accretion of material from one star to another, the merger of binary neutron stars, and the implosion and destruction of a massive star in a supernova explosion.

Many groups around the country are working on solutions to complex astrophysical problems. One of these, the Accelerated Strategic Computing Initiative (ASCI) Alliances Center for Astrophysical Thermonuclear Flashes at the University of Chicago, has developed FLASH, a parallel, adaptive-mesh simulation code to model the compressible, reactive flows found in astrophysical environments. This particular group is especially interested in simulating the physics of thermonuclear flashes on the surfaces and in the interiors of compact sources. Three phenomena that the code can address are Type I X-ray bursts, classical novae, and Type Ia supernovae. All of these phenomena are related to the accretion of mass from one member of a binary pair onto another. As is the case in many research fields in astronomy, an understanding of these large-scale events depends upon a thorough understanding of atomic physics and the ways in which matter behaves under very "unnatural" conditions, at least from our experience here on the Earth. The conditions simulated for these objects are so extreme that they are approached here on Earth only in thermonuclear explosions.

X-ray bursts have been detected, which are thought to be associated with neutron stars. The bursts have known rise times, or amount of time that passes until maximum brightness, and one effort of the University of Chicago group has been to model the flash as a helium detonation on the surface of a neutron star. The model shows that helium detonation can be triggered and account for the observed rise times.

In another effort, the role of Rayleigh-Taylor instabilities in the evolution of Type Ia supernovae is being modeled. The Rayleigh-Taylor problem consists of a dense fluid over a lighter fluid in the presence of a gravitational acceleration. Think of water on the ceiling of a cement basement. The two media—water and air—have widely different densities, but the drops that form and drip to the floor are a common example of this type of instability.

Alan Calder has explained the astrophysical significance of Rayleigh-Taylor instabilities: "Fluid instabilities and mixing are also expected to play a key role in the explosion mechanism of a Type Ia supernova. A subsonic burning front that begins near the center of a massive white dwarf is subject to [various] instabilities. Growth of these instabilities dramatically increases the surface area of the burning front. This increase in surface area increases both the burning rate and the speed of the front. The dependence of the speed of the burning front on fluid instabilities is one of the reasons a study of Rayleigh-Taylor instabilities is a key component in our efforts." Again, the power of this type of research is that, through modeling, it gives astronomers "virtual" access to a region that would otherwise be unknown: the core of a massive white dwarf star.

One of the great limitations of computational work in astrophysics is resolution. Astronomers working in this field must balance the need to model the system as realistically as possible with the finite amount of computer time they have to run the simulations. In the simple example just cited, relating the collision or merger of two galaxies, note that the simulation does not model each star as a point. The collision of two galaxies in which each star was represented by a point would take far too long to calculate to be of use to astronomers. So astronomers make decisions about what "resolution" is required. Is a physically different result obtained if each point represents 100 stars? 1,000 stars? 100,000 stars? Clearly, if each point represents 100 billion stars, then the merger of the two galaxies becomes the merger of two points, and the simulation is no longer informative. So astronomers must balance expediency with the need for a plausible solution. The work of Calder, just described, uses the adaptive-mesh capabilities of the FLASH code to see whether resolution has been a limiting factor in the modeling of Rayleigh-Taylor instabilities carried out thus far.

Finally, numerical work has increased our understanding of the merger of two neutron stars, one of the few astronomical events likely to produce measurable gravitational waves (see the discussion of the Laser Interferometer Gravitational-Wave Observatory [LIGO], Chapter 3). While previous calculations included only Newtonian hydrodynamics, the more recent calculation, carried out at the University of Illinois at Urbana, Champaign National Center for Supercomputing Applications (NCSA), included relativistic effects as well. As Calder points out, "General relativity predicts that a pair of neutron stars orbiting one another will radiate energy in the form of gravitational waves. This loss of energy will cause the stars to move closer and closer together, until they eventually collide." The new calculation has included relativistic radiation at the time of the merger, and the inclusion has resulted in the prediction of a different gravitational waveform. In this case, the simulation has provided a predicted "signature" that astronomers using the LIGO instrument can look for in their experimental results. To the surprise of astronomers, much like the mergers of galaxies mentioned earlier in this section, the mergers of neutron stars resulted in the formation of "tidal arms," eruptions of matter ejected from the interacting system.

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Chapter Two

Astronomical Technology and Techniques

From the earliest times, new astronomical instrumentation and techniques have brought about significant advances in our understanding of the universe. Early astronomers and astrologers used well-placed pairs of stones to mark the points on the horizon where the sun, moon, and stars rose and set at certain times of the year. Astrolabes and sextants, devices utilized since ancient times, allowed pretelescopic astronomers to accurately record the relative positions of the planets and stars in the sky. The first use of an optical telescope in the early seventeenth century by Galileo provided powerful observational evidence for a sun-centered solar system, and the invention of better optical telescopes and photography in the nineteenth century gave astronomers their first detailed views of distant galaxies and of the spectra of the stars in those galaxies.

The link between technological innovation and increased understanding has continued into the twentieth and twenty-first centuries. With the advent of enormous optical telescopes at the beginning of the twentieth century, and the development of telescopes and detectors sensitive to photons with wavelengths outside the tiny optical part of the electromagnetic spectrum in the 1930s, our understanding of the universe has grown in tandem with the development of new technologies (Figure 2.1). This chapter describes the state of the art in astronomical techniques, telescopes, and detectors and includes a description of the most advanced ground- and space-based telescopes in each portion of the electromagnetic spectrum.

Figure 2.1. The enclosure for the 4-m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) located in Chile is seen against the backdrop of the Magellanic Clouds and the Milky Way galaxy. Incredibly, this is not a composite image, and only starlight illuminates the scene. CTIO consists of a grouping of astronomical telescopes and instruments located 80 km east of La Serena, Chile, at an altitude of 2,200 m. The National Optical Astronomy Observatory (NOAO) operates CTIO. Courtesy of the Association of Universities for Research in Astronomy. Roger Smith, National Optical Astronomy Observatory, AURA, and the National Science Foundation.

TECHNIQUES

Telescopes themselves have not been the only driving force behind our increasing understanding of the universe. Advances have frequently resulted from the advent of new observational techniques, using existing telescopes in new ways. To cite a simple example, astronomers in ancient civilizations often used pairs of stones to designate the line of sight to important points on the horizon (e.g., the rising position of the sun on the summer solstice). They quickly learned that the use of stones at greater distances from one another enabled them to designate those rising and setting points more accurately (with higher resolution).

Interferometry is one technique that has transformed and continues to transform our understanding. In the twentieth century, early radio astronomers began to use the interference patterns generated by radio waves from astronomical sources to more accurately determine the positions of the sources and to make high-resolution images. For many years, the large amounts of glass and metal required to maintain the shape of telescopes as they steered around the sky limited the maximum size of the instruments. But recently the advancing sophistication of materials and computing power available to telescope designers have allowed them to develop much larger yet lighter structures, whose surfaces maintain their shape not by brute material strength but by the subtle constant monitoring and slight deformation of the reflective surface. In this section we explore some of the techniques that have changed the way we see the universe.

Interferometry

One way to increase the angular resolution of a telescope is to make the instrument larger. For optical telescopes, the ultimate examples of existing telescopes are the Keck I and Keck II. The largest steerable radio telescope,[1] the Robert C. Byrd Green Bank Telescope, was commissioned in August 2000 and is 100 m by 110 m. A second way to increase the resolution of a telescope is to use two or more telescopes together to detect the light from an astronomical source. The light is then combined, either electronically (for radio telescopes) or via carefully controlled optics (for optical and infrared telescopes). Combining light from several telescopes to produce a higher resolution signal is called *interferometry* (Figure 2.2).

Interferometry was pioneered first by optical astronomers in the early part of the twentieth century but was soon abandoned when the technique proved more daunting than simply building larger telescopes. The technique was revived by radio astronomers in the 1960s and has only today begun to be feasible for optical astronomy. Until very recently, combining the relatively tiny wavelengths of optical light properly was nearly a technological impossibility. The story is different for radio astronomers, who were trying to study celestial objects with

Figure 2.2. The European Southern Observatory (ESO) operates the Paranal Observatory in the Atacama Desert in northern Chile, seen here as photographed from the air. Paranal Observatory is the location of the four 8-m-diameter Unit Telescopes that have now been completed and seen first light. In combined mode, they have the sensitivity of a 16-m-diameter telescope. The concrete paths in the *lower left* corner of the image are tracks for three movable 1.8-m telescopes that will comprise part of the Very Large Telescope Interferometer (VLTI). Courtesy of the European Southern Observatory.

much longer wavelengths. For them, interferometry was the only way to rival the angular resolution produced by optical instruments. By placing two radio telescopes at a distance of 1 km from each other and using electronics to combine the signals, they could reproduce the same resolution a single telescope with a diameter of 1 km would yield. The price, however, is decreased sensitivity, since few of the radio waves that would have struck the "virtual" 1-km-diameter telescope strike the two smaller telescopes. The great advantage is very good resolution at a fraction of the cost of a 1-km telescope.

Interferometry had been limited to long-wavelength light (radio waves) because it is much easier to adjust the *wavefront* delays between telescopes for these low-frequency waves using low-tech electronics. Advances in optics and computing in the last decade, however, have made interferometric observations possible across the spectrum, into the infrared and even optical range. The coming decades promise to be an era of interferometric observations. Below, we describe some of the operational and planned telescopes that use this technique.

Aperture synthesis imaging uses the rotation of the Earth to sample different portions of the interference pattern as seen by a pair of telescopes in an array. As seen from space, the line connecting any two telescopes on the Earth will seem to rotate as the Earth rotates. Thus, any pair of telescopes detecting the interference pattern of light from an astronomical source is at every moment detecting a slightly different part of the pattern. The rotation of the Earth "synthesizes" a portion of a much larger telescope from every pair of telescopes in an array. One can imagine the synthesized telescope mirror or antenna as mostly blank space, with only a few arcs of reflective surface. For example, if two telescopes separated by 1 km were located at the North Pole and were observing the North star, the rotation of the Earth would synthesize the outer rim of a circular telescope with a diameter of 1 km. The addition of more telescopes between the two would "fill in" the aperture, both increasing the sensitivity of the telescope and better "synthesizing" the complete aperture. As one might imagine, the more completely the aperture is synthesized (by both the addition and the careful placement of additional telescopes), the better the quality of the final image.

The detected signal is an interference pattern, and it must be *Fourier transformed* to make an image of the source on the sky. Although optical and infrared interferometers are only now beginning to produce useful scientific data, the method has been proven for decades in the radio and holds great promise at all wavelengths. NASA plans to be able to detect planets around nearby stars in the next 10 to 20 years and to map the surfaces of these remote planets using interferometric techniques. In the next section, we describe four of the world's largest existing and planned radio interferometers and the handful of optical interferometers in existence or under construction.

Interferometric Telescopes

The Very Large Array (VLA)

Operated by the National Radio Astronomy Observatory (NRAO) in Socorro, New Mexico, the VLA celebrated 20 years of operation in 2000, having become fully operational in 1980. Since that time it has remained the largest radio telescope array ever constructed. The VLA is composed of twenty-seven 25-m radio dishes mounted on fixed piers; the telescopes are moved on railroad track arranged in a large Y shape (Figure 2.3).

The dishes are moved through four configurations, known as A, B, C, and D. The VLA spends approximately four months in each configuration. In the A configuration, each arm of the array covers nearly 13 km, and the largest distance between telescopes is about 35 km. In the D configuration the arms are about 1 km long.

The VLA has been able to stay on the cutting edge of astronomy by regularly upgrading receivers, amplifiers, and correlation systems

Figure 2.3. In the smallest configuration, the entire Very Large Array can be seen at once, as shown here in an aerial photograph. The VLA was dedicated in 1980 and just celebrated its 20-year anniversary. The twenty-seven 25-m-diameter radio telescopes operate as an interferometer to produce images that rival the resolution of the Hubble Space Telescope. Courtesy of the National Radio Astronomy Observatory.

and by improving data-processing techniques. Data reduction at the VLA has greatly benefited from the enormous advances made in computer hardware since 1980. Among the more recent additions to the VLA are the Q-band (7-mm) receivers, which give the array unprecedented angular resolution for a radio telescope. Since the VLA antennas do not have active optics systems, the antenna panels have been painstakingly diagnosed (using holography) and adjusted to perform at 7 mm. These receivers have pushed the VLA to its limits, and in the A-configuration, the VLA can achieve angular resolutions of 40 milliarcseconds, matching the resolution of the optical, space-based 2.4-m Hubble Space Telescope.

This example makes abundantly clear the enormous advantage that optical astronomers have in terms of resolution. A 2.4-m (space-based) telescope can match the resolution of a radio interferometer with antennas separated by 35 km! Why, then, should astronomers even try to achieve ultra-high resolution at radio frequencies? The reason is that many important phenomena are inaccessible to optical and infrared telescopes. Deeply embedded sources, like young stars, emit photons across the electromagnetic spectrum, but all of the optical and most of the infrared photons are absorbed by the cocoon of material that surrounds such objects. Radio observations are required to peel back the veil of dust and gas that hides these regions from view.

The Very Long Baseline Array (VLBA)

Also administered by the National Radio Astronomy Observatory, the VLBA is a 10-antenna array of 25-m radio dishes positioned at fixed locations across the United States. Spread from Mauna Kea in Hawaii to St. Croix in the U.S. Virgin Islands, the VLBA is capable of producing the highest-resolution images of astronomical sources. Its chief limitation is that only relatively strong and compact sources can be observed; as just described, while interferometers can have very high angular resolutions, they only have the sensitivity provided by the actual surface area of the telescopes in the array. Most observations with the VLBA have been of compact extragalactic objects (the near environments of black holes) and astrophysical masers (light of microwave wavelengths formed by the stimulated emission of radiation). More recently, interesting observations have been made of neutral hydrogen (HI) absorption against strong continuum sources found in remote galaxies.

The VLBA antennas match the size and performance of the VLA antennas, but their steering mechanisms are different, and their surfaces were designed to perform up to wavelengths as short as 7 mm and even 3 mm. The VLBA and VLA are often used together for projects in which increased sensitivity (collecting area) is important.

The Australia Telescope (AT)

The AT (Australia Telescope) is an eight-element radio telescope array controlled from near Narrabri, New South Wales. The AT provides high-resolution radio frequency imaging and spectroscopy from the Southern Hemisphere, an important consideration for astronomers who want to study the center of our own galaxy.

Six of the telescopes are identical in design and located within a 3-km area. The full array includes a single 22-m dish located about 120 km away from the compact array and the Parkes 64-m radio telescope located 321 km away. The array can observe objects similar in nature to those imaged by VLA but has significantly better spectral resolution and frequency bandwidth due to the combination of a modern *correlator* and advanced receiver construction. The array's most significant recent scientific contribution has been the mapping of the hydrogen content of the Large Magellanic Cloud, a companion to our galaxy. This study has discovered large holes in the hydrogen distribution created from supernova explosions and an intricate, filamentary structure to the hydrogen gas. The telescopes are often used in combination with other Australian telescopes to form the Australian Long Baseline Array, which (like the VLBA) can provide very high-resolution images of quasars and maser sources.

Atacama Large Millimeter Array (ALMA)

The ALMA is a millimeter and submillimeter wave interferometer that is now in the design development phase and is expected to see first light by 2009. ALMA is a collaborative effort between the NRAO, ESO, and a number of other European national astronomy agencies. The telescope is designed to be the premier instrument for millimeter and submillimeter wave radio astronomy, a wavelength where most of the photons in the universe are found, and one ideal for observing molecular material in our own and other galaxies. The array will include sixty-four 12-m dishes capable of collecting and imaging photons with wavelengths between 10 mm and 350 microns. The project will be constructed in Llano de Chajnantor, Chile, and the instrument will have a maximum resolution of 10 milliarcseconds.

ALMA will build on the success and experience of existing millimeter arrays in Europe and the United States, in particular, the Plateau de Bure interferometer (a six-element millimeter array located on a high alpine plateau in France), the Owens Valley Radio Observatory Millimeter Array (a six-element millimeter interferometer located near Big Pine, California, and operated by CalTech), and the Berkeley Illinois Maryland Association (BIMA) Array. BIMA is a nine-element millimeter interferometer operated by a consortium of three universities and located in the Sierra Nevada Mountains of California. Unlike these facilities, which are run by individual universities or consortiums of private institutions, ALMA will be a national observatory, like the HST or the VLA.

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Optical Interferometers

Navy Prototype Optical Interferometer (NPOI)

The NPOI is a collaborative effort of the U.S. Naval Observatory (USNO), the Naval Research Laboratory, and Lowell Observatory and is producing some of the first results in optical interferometry.

While the USNO interest in optical interferometry is primarily for astrometry (determining the precise positions of stars), the NPOI will also have powerful imaging capabilities. There are six movable mirrors (siderostats) with 50-cm diameters and baselines from 2.0 to 437 m, which send signals to 12-cm apertures. The array is sensitive to photons with wavelengths between 450 and 850 nm. NPOI has the same limitations of all interferometers. While it will make extremely high angular-resolution images (about 0.2 milliarcseconds), it will be able to image only relatively bright objects, brighter than about 7 magnitudes. In perfectly dark skies, the human eye can detect (though not resolve) sixth magnitude stars, which are only about 2.5 times brighter. The imaging array of NPOI will be able to resolve the disks of nearby stars.

Center for High Angular Resolution Astronomy (CHARA) Array

The CHARA Array is an optical and near-infrared interferometer currently under construction on Mount Wilson in California. The project is funded by Georgia State University and the National Science Foundation and is the only American university-based optical interferometer. In the final array, six to eight 1-m aperture telescopes will be arranged in a Y-shaped configuration (much like the VLA), and the instrument will have an angular resolution of 0.2 milliarcseconds in the visible part of the spectrum. The resolution will, of course, be slightly less in the near-infrared because of the longer wavelengths. The array will focus on the study of stars; although once operational, it will be able to study any optically luminous source.

Keck Interferometer

Keck I and Keck II operate currently as cutting-edge instruments, optimized for performance in the optical and infrared part of the spectrum. Planned adaptive optics systems (explained later in the next section) will improve the resolution to the *diffraction limit* of these telescopes, particularly in the near-infrared. However, the telescopes are planned also to be part of an array of optical telescopes called the Keck interferometer, a collaboration of CalTech, JPL, and the California Association for Research in Astronomy (CARA). The Keck interferometer promises to provide answers to fundamental questions about planetary origins and is partially funded by NASA's Origins Program. The completed array, which will include Keck I, Keck II, and four smaller 1.8-m telescopes, will have the angular resolution of an 85-m diameter telescope and the sensitivity of a 14-m telescope.

As with the VLT project, the addition of outrigger telescopes will improve the imaging capability of the Keck interferometer. Mirroring the development of radio astronomy, the first optical interferometers will be two-element systems, with additional elements (telescopes) added to the array as the technique is proven. To combine the light from the various telescopes, an optical system with mirror movements controlled to accuracies of 0.01 micron and updated on millisecond time scales will be required.

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Active and Adaptive Optics

Large objects are inherently structurally unstable. Skyscrapers, for example, wobble, but their design ensures that the building will hold together under all normal weather conditions, and a certain swaying is tolerated since even steel flexes when a force is applied. Large telescope mirrors are very heavy. Although they are made of glass, a thermal insulator, they still expand and contract slightly as the temperature changes. They also flex, depending on their angle relative to the ground. This flexing leads to distortions in the surface of the mirror. A further complication is that the Earth's atmosphere continually fluctuates in temperature and density, causing light traveling through it to be distorted from its original form. Historically, astronomers have had no fix for these problems beyond passive cooling of the mirror, the use of structurally rigid mirror supports, and the placement of telescopes on high mountains to decrease the influence of the atmosphere on the light they received. The techniques of active and adaptive optics now allow astronomers to overcome these limitations far more effectively.

Active optics provides a way of deforming a mirror to compensate for its inherent lack of structural rigidity. In adaptive optics, the optical elements of the telescope are instantaneously and continually adjusted to compensate for—in effect, to cancel out—the blurring effect of the Earth's atmosphere. Both active optics and adaptive optics use actuators (tiny pistons) and computers in a constantly monitored electronic feedback system to make minute adjustments to the shape of the primary and secondary reflective surfaces (Figure 2.4).

The main difference between the two techniques is that active optics systems make changes that are relatively slow. Active optics is intended to correct for the sagging of the telescope as it tracks an object across the sky or for the low-frequency components of the vibrations caused by the wind buffeting the telescope. In contrast, adaptive optics is intended to remove the effect of turbulence in the Earth's atmosphere and therefore makes much more rapid adjustments. The slower active

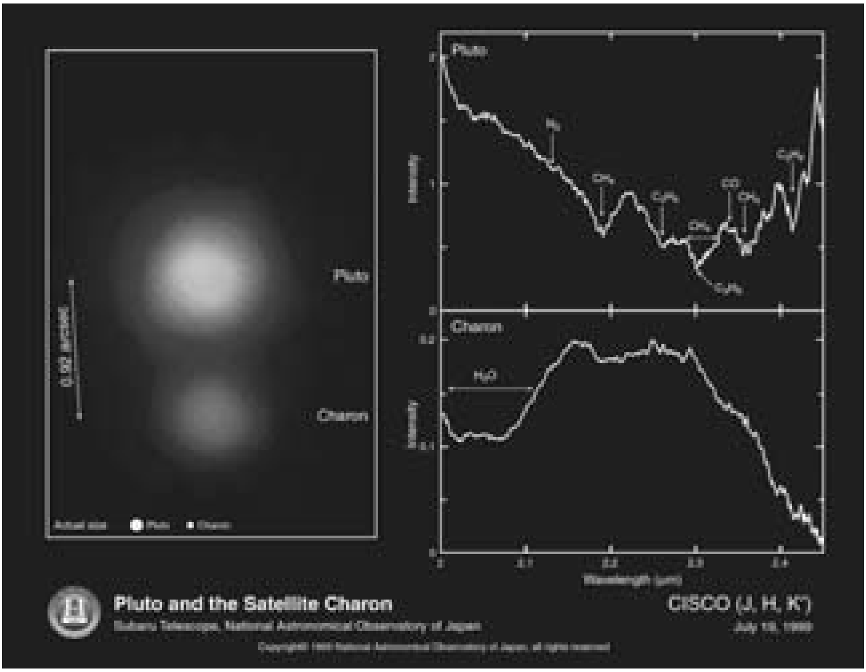

Figure 2.4. This image of Pluto and its companion Charon taken with the Subaru 8.3-m telescope (*left*) resolves the two bodies into distinct points of light. The accompanying spectra (*right*) show the importance of visually separating the two bodies, showing that the two objects have very different surface compositions, with Pluto showing evidence for solid ethane on its surface. Pluto and Charon have an apparent separation of only 0.9 arcseconds as seen from the Earth. Courtesy of the National Astronomical Observatory of Japan.

optics systems generally distort the primary mirror surface, while the more rapid adaptive optics systems typically make adjustments to smaller mirrors in the optical path of the telescope.

In addition to distortions of the primary mirror, most active optics systems also depend on movements of the secondary mirror, allowing the mirror to tilt and rotate interactively to adjust for errors in the primary surface. Active surfaces have been successfully tested on smaller telescopes and are now being installed on the next wave of large optical telescopes. The Keck active optics system adjusts the relative positions of the mirror segments and their shapes twice a second. The presence of an active optics system means that the mirror need not be as rigid as would have been otherwise necessary. An active optics system acts as a kind of "girdle," maintaining the ideal curvature of the mirror despite the tug of gravity. The mirrors on the Gemini telescope have 120 of these actuators behind them, capable of minute adjustments.

Active optics systems, sometimes known as "active surfaces," are not limited to use in optical telescopes. The Green Bank Telescope, the 100-m by 110-m radio telescope dedicated in August 2000, has an active surface controlled by over 2,000 actuators located at the junctures of the surface panels. As we build ever larger, ever thinner telescopes, we are becoming more and more dependent on active optical surfaces.

Adaptive optics systems must adjust the received light in such a way as to compensate for the distorting effect of the atmosphere. The light from distant objects arrives at the top of the Earth's atmosphere in a planar wavefront. The atmosphere distorts this wavefront through variations in the index of refraction. These variations, in a sense, slow down the light randomly across the wavefront. Adaptive optics systems compensate for this "rough" wavefront by adjusting the focal plane to compensate. Since the atmosphere varies quite quickly, the corrections to the optical wavefront occur on much shorter timescales than is the case with active optics; typically, thousands of adjustments are made each second. In addition to being faster, adaptive optics systems must also be able to control the surface of the primary or secondary mirror more finely. The incoming wavefront must be "sampled," or "sensed," with change-coupled devices (CCDs), and then corrections must be calculated and fed to a corrective mirror system. This sampling and correction of the wavefront should be done over approximately 20-cm subapertures on the mirror surface, since this scale corresponds to the typical size of the fluctuating regions in the atmosphere. For telescopes with 4-m size mirrors, adjustments to the primary mirror on this scale would require several hundred actuators. For larger telescopes like the Very Large Telescope and Gemini telescopes, thousands of actuators on the primary surface would be required (Figure 2.5). To overcome the need for a very large number of actuators, adaptive systems make adjustments not to the primary mirror but to the surface of the smaller secondary mirror.

The light from a single star in the field can be used to determine the distortions caused by atmospheric turbulence. This light is sent to a "wavefront sensor" that determines, on very short timescales, where and by how much the primary (or secondary) mirror must be distorted to produce a nearly pointlike image of the star.

Adaptive optics systems produce both a sharper and a brighter image. The blurring of the atmosphere spreads out the light of a star over (at best) 1 arcsecond or so. An operational adaptive optics system can concentrate that light into a point whose size is limited only by the diameter of the telescope. Alternatively, lasers can be used to create artificial beacons in the sky via scattered light. A laser aligned with the telescope effectively "samples" the atmosphere, and the mirror surface is adjusted to correct the detected scattered light into a pointlike source.

All of the large optical telescopes in existence or now under construction are candidates for adaptive optics systems. The Keck II telescope has recently provided practical demonstrations of its adaptive optics system.

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Figure 2.5. The completed and operational 8.1-m-diameter Gemini North telescope is shown here. Notice the minimal skeletal supporting structure for the primary and secondary mirrors. The primary mirror has a diameter of 8.1 m, and the secondary mirror can be seen in reflection. Courtesy of National Optical Astronomy Observatory.

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Other Techniques

Speckle Interferometry

Speckle interferometry is a recently perfected technique for removing the effect of the Earth's atmosphere, analogous to the technique employed by radio astronomers in their observations. Speckle observations consist of a large number of brief time exposures, typically taken every millisecond. Normal optical observations have sample times much longer, and the blurred, time-averaged star is all that is recorded in the image. The millisecond time exposures of speckle observations create a real-time record of the rapidly changing distortions caused by the Earth's atmosphere. The image of a star as seen through the atmosphere can be compared to a rock seen at the bottom of a wavy pool. Staring through the water, you would see a rapidly changing, distorted image of the rock. By using the information in a large number of pictures of the distorted rock, speckle techniques reconstruct the image of the rock as it really looks. Speckle techniques do—after the fact—what adaptive optics techniques attempt to do in real time.

For a 4-m-diameter telescope, the speckle technique can result in resolutions of 0.025 arcseconds from ground-based observations. This technique works best with point sources and binary stars, which are simple to analyze using Fourier methods. More complex *morphologies* and diffuse sources (sources that look like clouds) are much more difficult to image using speckle techniques. The Center for High Angular Resolution Astronomy at Georgia State University in Atlanta is one of the groups studying binary stars with speckle techniques.

Interest in speckle imaging has been heightened by the introduction of dark speckle. In this method, instead of adding the successive images in phase, the images are added in shifted phases so as to cancel the impact of a bright object at the center of the image. This process is easily accomplished digitally and is useful for searching for extremely faint objects, such as extrasolar planets, located close to stars.

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Computing

Since the time of Newton, scientists have known that, given sufficient computing power, they could accurately model the natural world using the deduced physical laws and known physical conditions. Such power to model the real world numerically is now found in a typical desktop computer. Software programs that correctly model the orbits of the planets and other solar system objects are even sold as entertainment. Astronomers have expanded these basic programs to study on their office personal computers (PCs) the physical processes taking place throughout the cosmos. Software has kept pace with the speed of computing hardware (and vice versa), allowing visualization, or interaction, with complex data sets. Artificial intelligence systems, designed to reduce the workload of astronomers, have been used with great effectiveness and are becoming more widespread in their application. The power of the PC has moved computing from a fringe activity of most astronomers to the very core of their daily activity.

Simulations

Many astronomical phenomena occur over very long or very short time periods. To understand these phenomena, many astronomers and astrophysicists depend on computer simulations to test their models of the universe. Luckily, the speed of computers and advances in computing languages have allowed more complete and easier-to-construct simulations of astrophysical phenomena. The increased speed of computers allows longer simulations or simulations with smaller time increments. This increases the accuracy of the simulations by more closely resembling the continuous temporal nature of reality. Improved computing languages have made the simulation of very complex physical systems easier to construct and implement.

As an example, magnetohydrodynamics (MHD) is a complex theoretical field that studies the motions of electrically conducting fluids as they interact with magnetic fields. In many astrophysical contexts, such interactions are important. Energetic stars ionize material in their vicinity, and the ionized material is often permeated by strong magnetic fields. The conditions are often more extreme near the centers of active galaxies, with larger energy sources and stronger magnetic fields. Computer simulations are often used to see how matter behaves under these extreme conditions and how a system will evolve, starting from some initial conditions. Some research groups even incorporate relativistic effects to simulate the near environments of black holes. These simulations allow astronomers to study the behavior of systems that could never be simulated in the laboratory. The frequent monitoring of the interaction of many particles is very computing intensive, and supercomputers, such as those found at the National Center for Supercomputing Applications, are used to run the codes.

The results of the simulations can then be compared to observations of astronomical sources to see if the theoretical evolution of the source matches the observed state of the system.

Visualization

Enormous multidimensional astronomical data sets are becoming more prevalent, and one of the most difficult tasks in analyzing them has been developing efficient ways to view and interpret data. Traditionally, astronomers have made images, or spectra, which are easily represented two dimensionally, such as brightness as a function of position on the sky or intensity as a function of wavelength. However, many data sets are three dimensional. For example, neutral hydrogen spectral data sets from the Very Large Array contain a spectrum (sometimes with hundreds of channels) at each spatial pixel in the map and can be large and difficult to manipulate and interpret. Visualization tools that allow astronomers to make integrations and slices through these cubes make it possible to look for trends in the data far more rapidly. These types of tools are only now becoming standard issue in data-reduction packages. One new software package, known as Interactive Data Language, or IDL, has a number of tools that allow scientists to customize the appearance of their data and visualize it using all of its dimensionality. For example, numerical modeling of astrophysical jets produces a large number of physical variables that vary with spatial location. IDL and other similar packages allow astronomers to display these physical variables and then explore their interrelationships. Researchers who use numerical modeling can form gridded volumes where each "voxel," or volume element (in effect, three-dimensional pixels), has a wide array of physical variables attached to it. These might include temperature, pressure, density, and so on. Using modern visualization tools, the relationship with temperature and pressure can be clearly investigated by displaying, for example, a difference of the two variables (after appropriate scaling). Negative values would then indicate regions of high temperature and low pressure, while positive regions would indicate the reverse.

This is only a hypothetical example, but it clearly suggests the power of these techniques. Other uses of these techniques include visualizing the spatial relationships between different molecular species, the three-dimensional distribution of galaxies in clusters. With the increasing computing power available to astronomers, we will begin to see three-dimensional animations showing the motion and evolution of celestial objects, finally bringing astronomy up to the level of the modern entertainment industry in terms of visual appeal. The difference will be that the astronomy visualizations represent reality, while entertainment visualizations (like those found in sci-fi movies) represent the work of the imagination.

Artificial Intelligence

With the growing number of large and complex surveys being carried out by the world's major observatories, the advent of artificial intelligence in astronomy is particularly timely. Since the turn of the century, astronomical data sets have become much larger, far too large for individuals to process. Thus, automated techniques employing artificial intelligence have become crucial to keeping up with the flow of incoming data.

One of the areas where automated techniques are already in use is the identification and classification of galaxies. The general galaxy classification scheme divides galaxies into spiral, elliptical, and irregular galaxies, and the exact brightness profile determines the subclass within those broad classes. Automatic scanning and classification techniques for galaxies will be instrumental in determining what most of the estimated 50 billion galaxies in the universe look like. Automated classification is also essential to the study of clusters of stars, where ultra-high-resolution telescopes outfitted with multiobject spectrographs will soon begin to generate an overwhelming tide of spectral line data.

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TELESCOPES

When most people hear the word *telescope*, they picture an optical refractor (a tube with lenses at each end) perched upon a tripod, ready to view the night sky. To an astronomer, the word *telescope* suggests something very different, depending on the type of astronomy he or she does. To a radio astronomer, the word might mean an array of 25-m-diameter parabolic radio dishes, arranged in a Y-shape in the middle of the New Mexico desert. To an infrared astronomer, the word might mean the soon-to-be launched SIRTF (Space Infrared Telescope Facility) telescope that will trail the Earth in a heliocentric orbit. A telescope is simply a device that collects and focuses any wavelength of electromagnetic radiation, whether gamma ray, X-ray, optical, infrared, or radio. In this section, we describe the capabilities of some of the world's most advanced existing and planned telescopes.

As complex as advanced telescopes are, they do essentially only two things: They *collect light*, and they *resolve objects*. The larger the telescope, the more light it collects (sometimes astronomers say that the telescope is "more sensitive"), and the better it resolves objects close to one another on the sky. The gains in sensitivity depend on the area of the telescope (area depends upon diameter squared), while the gains in resolution are based only on the diameter of the instrument. A telescope 10 times larger than another will be 100 times as sensitive but will have 10 times the resolution.

It should be apparent why astronomers want to build larger telescopes. The larger the telescope, the better it is able to do the things that astronomers desire: collect light and make sharp images. In detail, the resolution of a telescope depends not only on its size but also on the wavelength of the detected light. Radio waves, which are large, require larger telescopes to make sharp images. The effects of the atmosphere aside, even relatively small optical telescopes can yield sharp images because optical waves are about 100,000 times smaller than radio waves. To achieve the same resolution (sharpness) as an optical telescope, a radio telescope must have 100,000 times the diameter of its optical counterpart.

This inherent limitation on radio astronomy (and all long-wavelength astronomy) has meant that the optical part of the spectrum was the first to be probed extensively and that, to most people, "astronomy" means optical astronomy, and "telescope" means optical telescope. In addition, optical telescopes had a distinct advantage for early development in that the human eye can serve as a detector. Exploration of the universe at radio (and other) frequencies had to await the development of different types of telescopes and innovative techniques and detectors. In the past two decades, new methods and technologies have allowed astronomers to begin to explore most of the electromagnetic spectrum with both high sensitivity and high resolution.

The resolution of a telescope has one final limitation: the environment in which the telescope is used. This factor has been the driving force behind the newest telescope technologies to be developed. All ground-based telescopes, even those located on the highest mountains, are awash in the atmosphere of the Earth. So while the *sensitivity* of a telescope does depend on the diameter of a telescope squared, even for ground-based telescopes, the *angular resolution*, or the minimum angular separation between two stars that a telescope can detect,[2] runs up against the limitation of turbulence in the Earth's atmosphere. Thus, the comparatively small 2.4-m Hubble Space Telescope (located in orbit above the Earth's atmosphere) has better angular resolution than the enormous 10-m Keck telescopes atop Mauna Kea in Hawaii—at least when these telescopes observe without their adaptive optics employed.

As a result, large telescopes are the most desirable, because they produce the most sensitive, highest-resolution images. However, large telescopes also face inherent physical limitations. To properly focus light, a telescope has to maintain its perfect shape, even as it points around to different parts of the sky. And to achieve its theoretical resolution (that is, the angular resolution that corresponds to its diameter), a telescope must either escape the atmosphere or rapidly compensate for the turbulence that degrades the sharpness of an image. The quest for larger telescopes that can successfully overcome these limitations has been the driving force in telescope innovation in the twentieth and twenty-first centuries.

Ground-Based Optical and Infrared Telescopes

Optical telescopes have a long history, spanning nearly 400 years. In 1609, Galileo Galilei made the first ground-based optical telescopic observations of the heavens. He was struck by what he saw and remarked that the telescope revealed stars that could not be seen with the human eye alone. What he had experienced, of course, was the increased sensitivity and resolution provided even by his small optical telescope.

There are currently 46 operational telescopes with apertures (diameters of the primary mirrors) greater than 2.0 m and another 11 such telescopes under construction. Many of these telescopes have reflective surfaces and detectors that allow them to operate into the near-infrared part of the spectrum, but the presence of water vapor in the Earth's atmosphere limits the usefulness of ground-based observing far into the infrared. Sensitivity at infrared wavelengths requires space-borne, or high-altitude flying, telescopes. Seven of the 8 largest ground-based optical telescopes are planted in two locations, four on Mauna Kea, Hawaii, and three at Cerro Paranal in Chile.

While ground-based observations face limitations imposed by turbulence in the Earth's atmosphere, technologies such as speckle interferometry and adaptive optics can overcome these limitations. Because of the prohibitive cost and difficulty of repairing orbiting telescopes, ground-based telescopes, with their enormous collecting areas and relatively low cost, will continue to be at the forefront of astronomical observations for the foreseeable future. We now describe three of the five largest optical telescopes in the world and glimpse the science they are capable of doing.

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W.M. Keck Observatory (Keck I and Keck II)

The W.M. Keck Foundation has funded the construction of the two largest-diameter telescopes on the planet. The size of this pair of telescopes, operational since 1996, gives them unequaled resolution and sensitivity for ground-based optical and infrared observations of a variety of astronomical objects.

One telescope (Keck I) is primarily for use in the visible portion of the spectrum, while the second (Keck II) is primarily for use in the infrared. The pair is located on the summit of Mauna Kea in Hawaii. The telescopes' primary mirrors are each composed of 36 hexagonal mirror segments, which act together to form functional mirror surfaces 10 m in diameter. The California Institute of Technology, the University of California, and NASA jointly operate the observatory. The telescopes are fully equipped with instruments that provide imaging and high- and low-resolution spectroscopy. The telescopes have surfaces that can be slowly deformed via an active optics system, which maintains the shape of the mirror surface. Instrumentation that will be available soon includes an adaptive optics system developed by Lawrence Livermore National Laboratory.

By 2002, the light from each Keck telescope will be combined to form an optical interferometer. The two telescopes, acting together, will have the same angular resolution as an 85-m telescope and be capable (because the telescopes are so large, and therefore so sensitive) of studying very faint objects at high resolution. Eventually, four new 1.8-m telescopes (located near Keck I and Keck II) will be added into the Keck Interferometer to improve the image quality.

The Keck telescopes have already proved the continuing importance of large diameter, ground-based telescopes. Keck Observatory was the first to link gamma ray bursters with supernova-like explosions through their spectra. In addition, the observatory has provided spectroscopic confirmation of the distance of *high redshift* supernova explosions, helping to confirm the detection of an acceleration in the expansion of the universe. Because of their unequalled resolution and sensitivity, the Keck telescopes are beginning to produce interesting observations of very faint stars, called brown dwarfs. The study of these objects was previously difficult because their low temperatures and small surface area made them faint and difficult to separate from their nearby companion stars.

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The Very Large Telescope (VLT)

The Very Large Telescope under construction at Paranal in the high desert of northern Chile is designed to be the world's foremost optical interferometer. It is funded by the European Southern Observatory

(ESO), an intergovernmental organization for astronomical research based near Munich, Germany, and composed of eight member countries: Belgium, Denmark, France, Germany, Italy, the Netherlands, Sweden, and Switzerland. VLT consists of four 8.2-m telescopes, each of which can operate independently as a large-diameter optical telescope. The diameter of the individual telescope mirrors puts them in a four-way tie for the world's fourth-largest optical telescope.

The ESO has successfully constructed the first three of the four telescopes and is in the process of completing the final instrument. Ultimately, three movable 1.8-m telescopes will be added, along with the necessary infrastructure to operate the telescopes as a connected array, providing images with milliarcsecond angular resolution. The mirrors of the 8.2-m telescopes are a unique design, only 175 mm thick, making them more easily deformable by an active optics system. A recent VLT I-band (infrared) image achieved an angular resolution in the optical of 0.18 arcseconds.

The telescopes each can focus the light they collect in a number of ways: at the Cassegrain focus, behind the primary mirror; at the Nasmyth foci, located at both ends of the horizontal axis; or at the Coudé focus, a fixed focal point independent of telescope movement. Light is actually brought to the Coudé focus by moving it from one of the Nasmyth foci to the room below via a relay system. From here the light can be combined with that from the companion telescopes at the interferometric focus. The surfaces of the primary and secondary mirrors can be adjusted by an active optics system in response to gravity-induced distortions in the mirror shapes and temperature fluctuations. An exhaustive list of the instrumentation available on each of the telescopes, as well as an interactive diagram of the Paranal facility, may be found at http://www.eso.org/instruments/.

Though interferometric observations are years off, the VLT telescopes are starting their observational programs as individual telescopes. Spectroscopic observations with the VLT have recently confirmed the identity of four white dwarf stars, the old remnants of stars no longer fusing helium into carbon, in a globular star cluster. The Hubble Space Telescope first identified these objects in the globular cluster NGC 6397, but the VLT confirmed their identity as white dwarfs and allowed researchers to estimate their stellar parameters reliably.

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Gemini North and South

The fifth largest optical telescopes are the 8.1-m Gemini instruments, a joint project of the National Science Foundation and a host of international partners, including astronomical agencies representing England, Canada, Chile, Australia, Argentina, and Brazil. Administered by the National Optical Astronomy Observatory, these telescopes (like the HST) will provide access to world-class instrumentation for colleges and universities that have no in-house observatories. The first of the two telescopes, Gemini North, has been operational since June 1999 and is producing dramatic high-resolution images from its high-altitude home on top of Mauna Kea in Hawaii. (Figure 2.6). Gemini South is being constructed at Cerro Pachón, in Chile.

The Gemini primary mirrors (like the Very Large Telescope) are lighter and thinner than had been possible previously because their shape will be maintained by 120 actuators, tiny movable pistons mounted behind the primary mirror. In addition, Gemini North has an early operational adaptive optics system (Hokupa'a), built by the University of Hawaii, which was replaced in 2001 by the permanent system, ALTAIR (*alt*itude conjugated *a*daptive optics for the *i*nfra*r*ed). Like other adaptive optics system, these systems provide the potential to match and surpass the resolution of space-based telescopes like the HST. (Figure 2.7). Telescopes will have an adaptive optics system that will remove most of the blurring effects of the Earth's atmosphere. The goal is to achieve the theoretical best resolution of the telescope in the near-infrared.

Gemini South started observations in summer 2001, and a suite of instruments is under construction for use on both telescopes. The instruments cover the optical, near-infrared, and mid-infrared portions of the spectrum, with most of the instrumentation in the near-infrared. Astronomers will benefit from the presence of matched instruments in both the Northern and Southern Hemispheres.[3] Because Gemini is a service instrument, and not designed for a specific study, astronomers will use it to explore the full array of sources, from nearby planets to the most distant galaxies. Its flexibility and availability promise to make Gemini a worthy companion telescope to the HST.

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Figure 2.6. The Gemini North dome, shown here, is located in Mauna Kea, Hawaii, and was completed in 1998. The Gemini project is an international collaboration among the United States, the United Kingdom, Canada, Chile, Australia, Argentina, and Brazil that now operates two 8.1-m telescopes, one in each hemisphere. Germini South is located at Cerro Pachón in Chile. The modern Gemini domes are constructed to almost "disappear" during observing, allowing air to flow around the telescope and keep it at ambient temperatures. Courtesy of the National Optical Astronomy Observatory, the Association of Universities for Research in Astronomy, and the National Science Foundation.

Overwhelmingly Large (OWL) Telescope

The European Space Organization is exploring the feasibility of building a 100-m diameter, fully steerable optical telescope to be known as the OWL Telescope. The telescope is revolutionary for many reasons, one of which is that it will be 10 times larger than the largest existing optical telescope. Historically, telescopes have tended to double in size, each new telescope being two times larger than its predecessor. Sensitive to objects as faint as thirty-seventh or thirty-eighth magnitude, with an angular resolution of a few milliarcseconds, OWL would open new vistas in astronomy. For comparison, a 4-m-diameter telescope (which is almost twice the diameter of the HST) has a magnitude limit of about 26 magnitudes. And each step in magnitude

Figure 2.7. Reproduced here is a composite high-resolution image taken with Gemini's adaptive optics system. It shows a planetary nebula (BD + 303639), with its central star visible in the center. The full width at half-maximum (FWHM) of the stellar image is 0.083 arcseonds, with resolution only a factor of 2 below that of the HST in the optical. Courtesy of the Gemini Observatory, the National Science Foundation, and the University of Hawaii Institute for Astronomy.

represents an object that is 2.512 times as faint. So the OWL telescope would be sensitive to sources $(2.512)^{12}$ or 63,000 times as faint as a 4-m telescope. The study of the surfaces of other stars, imaging and spectroscopy of extrasolar planetary systems, and the study of high-redshift supernovae are just a few of the possibilities.

Why is such a large telescope required? This is, why can't the same goals be achieved by interferometry? While interferometers provide the resolution of a telescope with much larger aperture, they do not provide the same increase in sensitivity. Sensitivity requires surface area, and OWL will have an overwhelming amount of surface area. The goal of the OWL (originally dubbed the WTT for Wishful Thinking Telescope) is to be able to make spectroscopic observations (which require more sensitivity) of the faintest objects observed by the Next Generation Space Telescope (NGST), an instrument discussed later in the chapter.

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Other Ground-Based Telescopes

There are three "windows" to electromagnetic radiation in the Earth's atmosphere, roughly at optical, near-infrared, and radio wavelengths. Because a telescope's resolving power depends on both the size of the instrument and the wavelength of observations, high-resolution studies were first made at optical and infrared wavelengths. High-sensitivity and high-resolution radio astronomy was slowed by the need for proportionately larger—and therefore more costly—telescopes. In this section, we describe the largest, most sensitive, and highest-resolution radio telescopes. We also describe the recently dedicated LIGO telescopes, which are sensitive to a different type of emission altogether: gravity waves.

A wide variety of radio telescopes currently operate from the Earth's surface. The main reason that radio astronomy is performed from the ground rather than from satellites is that radio telescopes must be much larger than their optical counterparts to produce high-resolution images; however, lightweight materials and precise remote control of telescope orientation are making large radio telescopes in orbit feasible. Gossamer antennas, and either thin foils or meshlike grids are the two current favored technologies. The Japanese have successfully deployed an orbiting radio telescope that has been used in conjunction with ground-based radio telescopes to make interferometric observations.

Arecibo

With radio telescopes as with optical telescopes, it is all about size. The Arecibo radio telescope is by far the world's largest *single-dish* antenna. Located in a jungle valley on the island of Puerto Rico, the dish is 305 m in diameter and, in the last few years, has been featured in the climactic scenes of the James Bond movie *Golden Eye* as well as the science fiction movie *Contact*. Completed in 1963, it has made many discoveries, including the detection of millisecond pulsars, the first binary pulsar, and the first detection of a planetary system outside our own. The telescope has also been used to search for signs of life in our galaxy.

The Arecibo instrument has had two major upgrades since its dedication. A high-precision reflective surface was installed in 1974, and in 1997, the entire reflecting surface was shielded from ground radiation and new electronics installed to improve effectiveness and efficiency. The signals detected by the radio dish are focused below a 900-ton platform, which hangs 450 feet above the surface. Although the large (primary) surface is not steerable, the azimuth arm located below the platform suspended above the dish allows Arecibo to cover more of the sky than just the region immediately overhead. Electronics located here include a new planetary radar transmitter and helium-cooled radio-frequency detectors, which can be used for imaging and spectroscopy. Because of its enormous size, Arecibo is the most sensitive radio telescope on the planet—almost 10 times as sensitive as the recently dedicated 100-m-by-110-m Green Bank Telescope (GBT), which, however, is fully steerable.

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Green Bank Telescope (GBT)

Operational since August 2000, the Green Bank Telescope, operated by the National Radio Astronomy Observatory, surpasses the Effelsberg 100-m as the largest steerable radio telescope in the world (Figure 2.8). Capable of observing at the highest possible radio frequencies, the GBT observes (under ideal conditions) at frequencies up to 80 GHz. The GBT has an unusual shape, resembling the small dishes that attach to homes to receive satellite television. Most radio telescope primary surfaces are paraboloid in shape, but the GBT surface is just a portion of such a paraboloid—effectively a 100-m-by-110-m paraboloid section. Traditional radio telescopes support their detectors and secondary mirrors over the center of the reflective surface, blocking 10 to 15 percent of the aperture (light collecting ability), but the unique design of the GBT leaves the aperture unblocked, increases the useful area of the telescope, and gets rid of the internal reflections and diffraction that can complicate the reduction of radio data. In early 2001, the GBT in conjunction with Arecibo made high-resolution surface radar maps of the planet Venus. Early scientific results from the GBT have been stunning, and it promises to be a productive and powerful instrument in the decades to come.

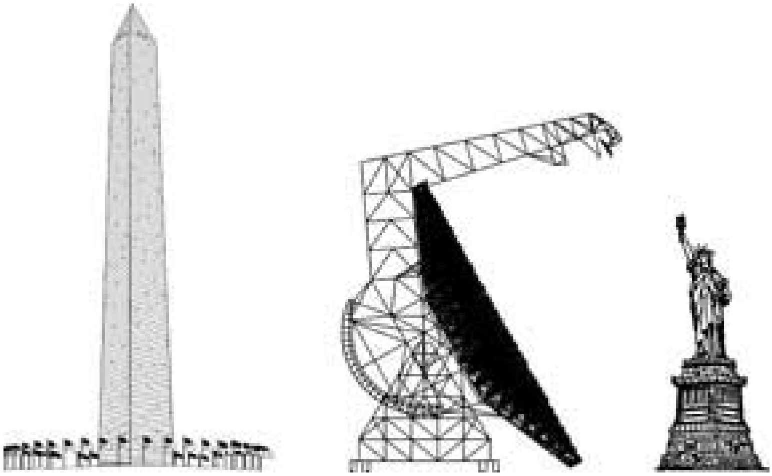

Figure 2.8. Dedicated in the fall of 2000, the Green Bank Telescope (GBT) is the world's largest fully steerable radio telescope. It is located in Green Bank, West Virginia. The diagram shown here indicates its impressive 110-m size, as compared to the Washington monument and the Statue of Liberty. The GBT is a facility of the NRAO. Courtesy of the National Radio Astronomy Observatory.

The GBT also benefits from having an active (correctable) surface, much like the Effelsberg 100-m and the largest new optical telescopes. To this end, the GBT uses a laser-ranging system to determine the deformation of the surface during observations. Mirrors are arranged around the perimeter of the dish, and lasers on the ground. The combination serves as an accurate set of range finders, so that the actual shape of the GBT primary surface can be compared to a model of the ideal surface, and then corrections can be applied via a system of actuators.

Two thousand panels make up the telescope's reflective surface. Because the GBT was designed with an active surface, the support structure is less rigid—and less heavy—than the structures of most radio telescopes. In conventional telescopes, pistons are designed to bear weight along their axis but not perpendicular to that axis. Since the GBT must point at all regions of the sky above 5 degrees from the horizon, the 2,209 actuators (pistons) that control the GBT surface must bear weight along both axes and had to be specially developed.

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Laser Interferometer Gravitational Wave Observatory (LIGO)

Dedicated in February 2000, LIGO promises to open an entirely new window for ground-based astronomers: the observation of gravity waves. *Gravitational wave* telescopes look nothing like other telescopes. The two LIGO facilities built thus far, in Hanford, Washington, and Livingston, Louisiana, are large L-shaped concrete structures, each arm of the L 4 km (2.5 mi.) in length. Two facilities have been built as a rigorous means of discarding signals that arise locally because of vibrations. Only gravity waves detected at both LIGO locations are considered valid objects for study. Within each arm is a 4-foot diameter vacuum pipe, and the juncture of the two arms houses a beam splitter and two partially reflecting mirrors that allow the laser beam to be sent down two perpendicular tubes, reflect, and then recombine before striking a detector. The two waves interfere with one another constructively if they are in phase and destructively if they are out of phase. The equipment is tuned so that the waves destructively interfere, producing a black spot. If a gravity wave passes the equipment, the length of the two tubes changes slightly (in accordance with general relativity), and a constructive interference pattern is detected.

Laser beams maintained in the vacuum pipe are able to detect tiny changes in the length of either arm. The change in length is due to the gravitational distortion in space and is, therefore, the expected signature of a gravity wave. Moreover, the change in length in two perpendicular directions should be opposite. That is, if one of the legs of the L decreases in length, the other should increase. The changes in length of the 4-km beam that result from the passage of a gravity wave will be miniscule, about 10^{-16} cm, or one part in 10^{21}, yet still detectable.

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Space-Based Telescopes

Most wavelengths of light (other than optical, the near-infrared, and longer-wavelength radio waves) are absorbed by the Earth's atmosphere. Atmospheric molecules absorb light with short wavelengths, fortunately protecting us from genetic damage caused by high-energy ultraviolet and gamma ray photons but also limiting our ability to study space. In addition, the Earth's atmosphere distorts the light that does make it through the atmosphere from distant objects. Much as the water in a swimming pool disturbs our view of objects on the bottom of the pool, so our atmosphere disturbs our view of the universe.

The only way to detect most of the photons coming from space is to get above the Earth's atmosphere, either using balloons or, more recently, high-flying or orbiting platforms. NASA in the United States has been at the forefront of the funding and operation of space-based observatories, and the NASA Great Observatories program has been successful in probing the universe at a variety of wavelengths across the electromagnetic spectrum from above the Earth's atmosphere. In this section we describe the telescopes and programs that have peeked at the universe from outside the protective blanket of our atmosphere.

Stratospheric Observatory for Infrared Astronomy (SOFIA)

Housing a telescope in the fuselage of an airplane flying in the stratosphere is not a new idea. Ever since the late 1960s, airplanes have been used to lift telescopes above most of the blurring and absorbing effects of the Earth's atmosphere. The most recent incarnation of this idea was the Kuiper Airborne Observatory (KAO), which was decommissioned in 1995. The newest instrument is SOFIA, the largest airborne telescope in the world. A joint project of NASA and DLR (German Aerospace Center), the German space agency, it will be developed and operated for NASA by a team of industry experts led by the Universities Space Research Association (USRA) and will make observations that are impossible for even the largest and highest of ground-based telescopes.

A Boeing 747 will carry the 2.5-m-class telescope, about the size of the Hubble Space Telescope, and fly at altitudes between 39,000 and 41,000 feet. SOFIA will be outfitted with detectors that will allow it to make observations in the near-, mid-, and far-infrared. The ability to observe in the far-infrared without sending a spacecraft into orbit is a unique capability of SOFIA.

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NASA Great Observatories

The Great Observatories are four orbiting telescopes developed and funded by NASA: the Hubble Space Telescope (HST), the Compton Gamma Ray Observatory (CGRO), the Chandra X-ray Observatory (CXO), and the Space Infrared Telescope Facility (SIRTF), launched late in 2001. The goal of the Great Observatories program has been to construct a set of telescopes outfitted with equipment designed to carry out astronomical studies over many different wavelengths. Perhaps the most important aspect of the program is the overlapping of the observational phases of the four missions, so that simultaneous, multifrequency, space-based observations have been possible.

The Hubble Space Telescope (HST)

Designed to observe ultraviolet, optical, and near-infrared light, Hubble is a 2.4-m telescope more than five stories tall and weighing 12 tons. The telescope is named for American astronomer Edwin P. Hubble, who first discovered that galaxies are distant groupings of stars, rushing away from us at great velocity due to the expansion of the universe. This telescope is probably the only astronomical instrument that can be said to be a household word. HST was carried into orbit and deployed on April 25, 1990, from the space shuttle *Discovery.* It took more than 20 years to move Hubble from concept to operational readiness in low-Earth orbit.

The HST is outfitted with a variety of instrumentation, making possible spectroscopic and imaging observations in the ultraviolet, optical, and infrared. Hubble's Wide Field/Planetary Camera 2 (WF/PC2) instrument has produced some of the most stunning images released to the public. The optics in WF/PC2 were designed to compensate for the error in the production of the HST primary mirror, deployed in 1990, which was made 2 microns too flat at its edge. WF/PC2 consists of three wide-field cameras in an L-shape with a smaller camera (the planetary camera) placed in the nook of the L. This placement of cameras gives HST images from WF/PC2 their distinct "L-shaped" appearance and allows a balance between wide-field imaging (seeing a lot of the sky) and high resolution (seeing detail).

Other instrumentation aboard HST includes the Space Telescope Imaging Spectrograph (STIS), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Faint Object Camera (FOC). STIS is the workhorse spectrograph of the HST, enabling astronomers to break starlight into its component wavelengths and determine the composition and motion of stars. NICMOS is a combined imaging (picture-making) and spectroscopic (spectrum-making) instrument, designed to be sensitive in the near-infrared part of the spectrum. The FOC is tuned to observe and detect only objects fainter than twenty-first magnitude, or about a million times fainter than those visible to the human eye. The Corrective Optics Space Telescope Axial Replacement (COSTAR) instrument was installed during the first servicing mission to correct the optics for the FOC and will be removed when FOC is decommissioned during the next HST servicing mission.

Results from the HST are too numerous to describe thoroughly, and a visit to the Space Telescope Science Institute World Wide Web (WWW) site (see References) will allow the reader to browse the most recent scientific results. However, one particular project deserves special notice because of the unrivaled sensitivity of the image resulting from the length of the exposure. Former Director of the Space Telescope Science Institute (STScI) Robert Williams decided to use his director's discretionary time (150 consecutive orbits) to observe a single small patch of sky.

Unlike most HST images, the raw results of the Hubble Deep Field (HDF) were made immediately available to the astronomical community. Several thousand never-before-seen galaxies are visible in this "deepest-ever" view of the universe, called the Hubble Deep Field (Figure 2.9). Williams's observations have provided the most sensitive, highest-resolution images of this part of the sky ever made. The public accessibility of the HDF images has inspired a series of follow-up observations at other wavelengths to determine, for example, what fraction of galaxies observed at this early time in the universe are "active galaxies" as indicated by their radio and X-ray emission.

The Compton Gamma Ray Observatory (CGRO)

In an effort to cool down the heated nuclear arms race in the 1960s, the United States and the Soviet Union agreed to stop performing atmospheric tests of nuclear weapons. Since these explosions produce large amounts of gamma rays, they could be detected by orbiting gamma ray detectors. To monitor compliance with the atmospheric test ban, the U.S. military launched some of these satellites and soon were detecting a gamma ray burst at the rate of about one a day. This observation triggered intense communications with the Soviet leadership, who steadfastly denied carrying out atmospheric tests. Indeed, it was soon determined that the bursts were not originating from nuclear explosions on the ground but were coming from some celestial source or sources. The second of the great observatories, the Compton Gamma Ray Observatory, has studied these sources in detail. The CGRO has helped to determine that so-called gamma ray bursts come from energetic activity originating in the farthest reaches of the universe.

Launched in 1991, the Compton Gamma Ray Observatory consisted of four separate instruments sensitive to gamma rays with differing energies mounted to a single satellite frame: the Burst and Transient Source Experiment (BATSE), the Oriented Scintillation

Figure 2.9. The Hubble Deep Field (HDF) was made using director's discretionary time during Cycle 5 and represents approximately 10 days of observing time (150 orbits). Some of the galaxies seen in the image are relatively nearby, but a fraction of the smaller galaxies observed are among the most distant objects we can see with optical telescopes—galaxies that formed within 1 billion years of the Big Bang. The galaxies seen in this image seem to be smaller and more "disturbed" than galaxies that we see in the current universe. Courtesy of Robert Williams, Hubble Deep Field Team, StScI, and NASA.

Spectrometer Experiment (OSSE), the Imaging Compton Telescope (COMPTEL), and the Energetic Gamma Ray Experiment Telescope (EGRET). Due to a gyro failure on the satellite, NASA had to perform a preemptive reentry of the satellite for safety reasons in June 2000. BATSE was an all-sky monitor sensitive to photons with energies from 20 to 600 KeV, consisting of eight detectors. OSSE provides spectroscopic information in the 0.05 to 10 MeV region. The COMPTEL instrument could image photons between 0.8 and 30 MeV, and finally EGRET detected the most energetic photons with energies from 20 MeV to 30 GeV.

Because of their high energy, gamma rays (like X-rays) are not easily bent, or reflected, which necessitates some unique detector designs. There are three basic ways to observe gamma rays. First, one can form a dense material that either partially or totally absorbs the gamma ray. Second, using very dense material, one can block out most of the sky, thereby receiving gamma rays from only one direction in the sky. This method can provide crude directional information. Finally, for very energetic gamma rays, a spark chamber can be made, in which the gamma ray is converted to electron-positron pairs, which can be detected and which can then lead to some determination of the direction of the high-energy photon.

One of the most exciting results to come from the Compton mission was from the BATSE experiment. This instrument was designed to follow up on the mid-1960s detection of bursts of gamma ray radiation that occur about once per day. The BATSE detectors are built around sodium iodide crystals, designed in such a way to produce a flash of light when they are struck by a gamma ray. The signals from the eight detectors, located at the corners of the spacecraft, are analyzed simultaneously to determine the arrival time and direction of the gamma ray. Before BATSE, the nature of "gamma ray bursters" was practically unknown. BATSE provided an all-sky map of the sources, showing that bursters are distributed uniformly across the sky and are likely cosmological (very distant) in origin.

The next large gamma ray telescope in orbit will be the Gamma Ray Large Area Space Telescope, or GLAST. This telescope will provide much more collecting area than CGRO and yield increased spectral resolution in the gamma ray part of the spectrum as well as improved time resolution for studying the gamma ray burst sources. Launch of this new telescope is currently scheduled for 2005 and will involve international partners as well as NASA scientists and university researchers. GLAST will make up for the most serious shortcoming of the current generation of gamma ray telescopes, poor angular resolution, and be capable of locating gamma ray sources with accuracies of between 30 arc seconds and 5 arc minutes.

Advanced X-Ray Astronomy Facility (AXAF)/Chandra

Launched on July 23, 1999, the third of NASA's "great observatories," the AXAF/Chandra is designed to study our universe in X-rays. The working name of the observatory was the Advanced X-Ray Astronomy Facility, but the telescope was renamed (after an open naming contest) in honor of the famous Indian American astronomer Subrahmanyan Chandrasekhar. Chandrasekhar provided a great deal of the theoretical underpinnings that describe the emission of X-rays from astrophysical objects; he won the 1983 Nobel Prize for his work.

Because of the high energies of X-ray photons, X-ray telescopes cannot be designed like optical telescopes. If X-ray photons strike a mirror surface at too great an angle, as measured from the mirror, they pass right through, depositing some of their energy in the mirror material. However, if the X-ray photons strike the mirror at a small (grazing) angle, they can be redirected, or focused, in a detector. For this reason, X-rays are focused in Chandra by a series of grazing reflections (Figure 2.10).

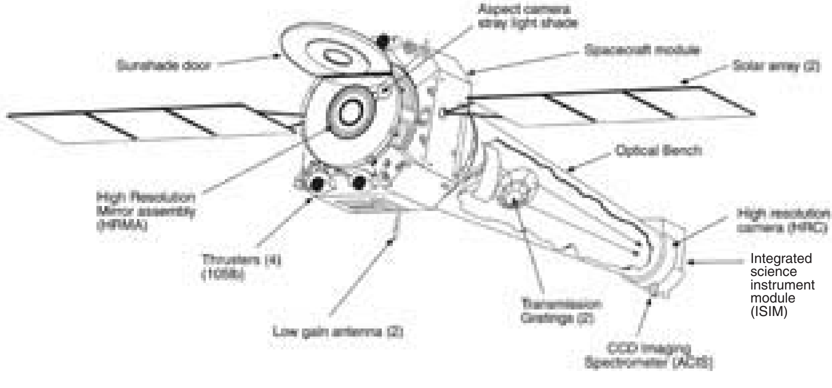

Figure 2.10. A schematic diagram of the Chandra/AXAF spacecraft. The Chandra spacecraft is typical in providing a support structure for the imaging equipment on board (optical bench), a power generation system (solar array), and a way to protect the sensitive equipment from solar radiation (sunshade door). Energetic X-ray photons strike a nested set of mirrors at small angles so that they are reflected into the focal plane. Courtesy of the Chandra Science Center.

The instrumentation on Chandra includes the High Resolution Camera (HRC), the Advanced CCD Imaging Spectrometer (ACIS), and two high-resolution spectrometers: the High Energy Transmission Grating Spectrometer (HETGS) and the Low Energy Transmission Grating Spectrometer (LETGS). The HRC is the instrument that produces high-resolution "pictures" of sources as seen in X-rays, and the three spectrometers divide up the electromagnetic spectrum into smaller pieces so that astronomers can determine the presence, abundance, and motions of particular atoms and molecules.

The goal of the Chandra mission has been to increase both the angular resolution and spectral resolution available to X-ray astronomers. The bulk of Chandra's results so far have been related to stars and galaxies (Figure 2.11). Supernovae, supernova remnants, neutron stars, black holes, and certain magnetic dwarf stars all produce X-rays. Within just the first month of launch, Chandra produced images of the neutron star associated with the Cassiopeia A supernova remnant. Studies of supernovae are important to an understanding of the chemistry of the interstellar medium because all of the heavy elements found on Earth, such as iron, silicon, and gold, were created in supernova explosions.

Chandra has confirmed that the X-ray emission coming from the region surrounding the black hole at the center of the Andromeda galaxy (our closest galactic neighbor) originates from material far cooler than predicted by current models for black holes of this type. Astronomers believe that the mechanism by which material is funneled from the surrounding interstellar medium into the black hole must now be reworked, showing once again that observing even nearby, familiar sources with new instruments can lead to striking discoveries.

Space Infrared Telescope Facility (SIRTF)

The fourth and final Great Observatory was scheduled for launch in April 2003. This instrument will provide a view of the universe in the infrared, with wavelength coverage from 3 to 180 microns, a portion of the spectrum dominated by emission from dust and relatively cool objects. It was planned to be deployed in an Earth-trailing, heliocentric orbit and have a lifetime of 2.5 to 5 years; it will employ the next generation of large-format infrared detectors. As a fundamental research tool in NASA's search for Origins Program (see Chapter 7), the 85-cm-diameter telescope is designed to study brown dwarfs (failed stars), extrasolar planets (planets orbiting stars other than the sun), protoplanetary dust disks (presolar systems), and galaxies just

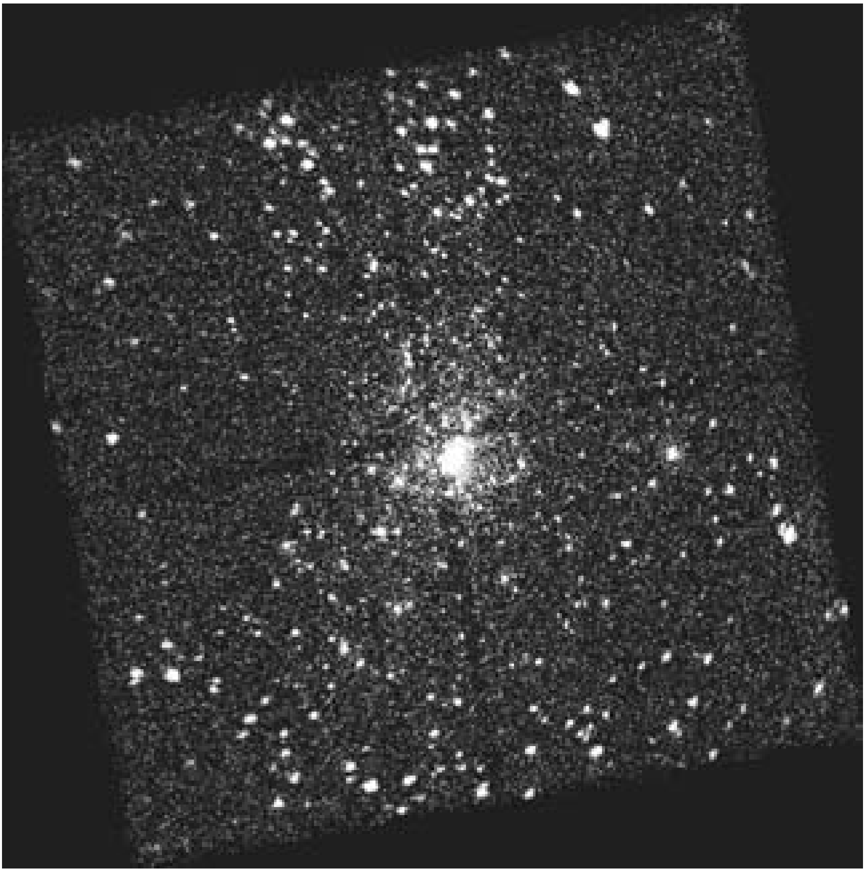

Figure 2.11. Recently the orbiting Chandra X-Ray telescope imaged the thousands of young stars in the Orion star-forming region. The vast improvements in X-ray sensitivity and resolution represented by Chandra made this image possible. Because the Orion nebula and the stars that power it are relatively close to Earth (about 1800 light years), it is one of the most well-studied regions of star formation. Courtesy of the Chandra Science Center.

forming at very early times in the universe. SIRTF will be capable of measuring light (photometry) with the Infrared Array Camera (IRAC) and the Multiband Imaging Photometer for SIRTF (MIPS) and performing spectroscopy and spectrophotometry with the InfraRed Spectrograph (IRS).

SIRTF will be able to detect large, warm planets around nearby stars. While most of a solar-type star's energy is radiated in the optical part of the spectrum, planets reradiate their energy in the infrared. Galaxies undergoing collisions experience a heating of their dust from tidal forces (the differential pull of gravity on an object), star formation processes, and other mechanisms. The dust then releases this energy into the universe in the form of infrared light. So much light is given off that galaxies of this type are called ultra-luminous galaxies. The size of the SIRTF mirror and the high efficiency of its detectors will allow astronomers to detect these sources at vast distances and study the nearer ones in great detail. SIRTF will also enable studies of Active Galactic Nuclei (AGNs), which emit X-rays, radio waves, and optical light and are likely powered by black holes.

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Cosmic Background Explorer (COBE)

Since the discovery of the cosmic microwave background (CMB) in the 1960s, and the subsequent proposal that the CMB is a signpost of the Big Bang, astronomers have tried to determine its properties and its precise distribution on the sky. Launched in 1989, the Cosmic Background Explorer was developed to explore the remnant diffuse infrared and microwave background radiation from the early universe. The Differential Microwave Radiometer (DMR) detectors (which look for tiny variations in the background temperature) determined that the CMB is not entirely isotropic (same in all directions) but has variations on the sky at the level of 1 part in 100,000. These variations in temperature indicate that the early universe was not smooth but in some sense "patchy." This COBE result set the groundwork for the later balloon-borne experiments described in Chapter 1.

One of the COBE mission's main objectives was to determine the exact spectrum (brightness as a function of wavelength) of the CMB radiation. Fundamental physics tells us that the spectrum of a hot object (sometimes called a *blackbody*) follows the Planck function and that the wavelength at which a hot object gives off most of its radiation determines its temperature. The COBE results fixed the temperature of the universe to be 2.728 degrees K above absolute zero. The universe is filled with the remnant heat from the Big Bang, and today this radiation is very cold, due to the expansion of the universe. By carrying this value back in time, cosmologists can help characterize the conditions in the early universe soon after the Big Bang.

COBE was also able to map the distribution of the CMB radiation with an effective angular resolution of 10 degrees and to determine that we are moving with respect to this radiation. This motion is dominated by our local group of galaxies, which is moving toward the center of the nearest galactic supercluster. After subtracting the effect of our motion and the microwave emission coming from the disk of our galaxy, the remaining fluctuations (less than 1 part in 100,000) show the early universe density and temperature fluctuations that gave rise to the universe we see today.

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Microwave Anisotropy Probe (MAP)

The Microwave Anisotropy Probe, was launched in April 2001, as a successor mission to COBE to measure and characterize the properties of the cosmic microwave background. The final results of the MAP mission will address the following cosmological questions: (1) When did the first galaxies form? (2) What are the values of the physical parameters that govern the expansion of the universe? (3) How did galaxies first form?

The MAP has begun to make full-sky maps of temperature fluctuations in the CMB with sensitivity and angular resolution exceeding the COBE results. The angular resolution of the five instruments ranges from about 0.2 to about 1 degree. For comparison, the full moon takes up about 0.5 degrees on the sky. The satellite is in a unique location in the solar system, called the *L2 Lagrangian point*, located 1.5 million km beyond the Earth on a line from the sun passing through the Earth. This gravitationally stable location allows a satellite to maintain its position for up to 20 or so days with only minor course and altitude corrections required.

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Next Generation Space Telescope (NGST)

NGST is to be built and launched by NASA as early as 2007. The telescope will be in many ways the successor to the Hubble Space Telescope and should come on line as the HST is being decommissioned. The NGST will be sensitive to photons in the near- and mid-infrared in the wavelength range from 0.6 to 20 microns and will need to be as sensitive as the largest ground-based telescopes and have resolution matched to the Hubble Space Telescope. Because of the longer wavelengths that NGST will detect, it will need to be proportionally larger in diameter than the HST, which is intended to detect smaller wavelength optical photons. The NGST will study the formation of stars and planetary systems and the formation and evolution of galaxies.

The NGST will have a diameter of 8 m, which will require that the mirror surface deploy after launch. One of the benefits of the NGST will be its large collecting area, making the telescope more sensitive. Another way to think of sensitivity is that a larger telescope can make the equivalent observation in a shorter amount of time. For example, an 8-m telescope can carry out an observation in a fourth of the time an equivalent observation would take on a 4-m telescope. Thus, the NGST will make observations that are impractical on a smaller telescope.

Several schemes for the deployment of such a large primary mirror are being investigated, but all involve the opening of a "folded" mirror as the telescope is boosted to its orbit at the L2 Lagrangian point, the same location proposed for the MAP mission.

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IMAGING DEVICES, DETECTORS, AND OTHER TECHNOLOGY

The first, and still most widely used, astronomical telescope/detector system is the human eye. With a relatively small aperture, and able to detect light only in the visible part of the spectrum (400–700 nm), the human eye has serious limitations. In this chapter so far we have described the techniques and telescopes that have enhanced our ability to see the universe. We now turn to the latest revolutionary detectors and other technologies that have improved that view. These include imaging devices such as charge-coupled devices, or CCDs, now commonly found in digital cameras, new radio-frequency detectors such as bolometers, bolometer arrays, and hot electron bolometer mixers, and techniques now enabled by such technological advances as multiobject spectroscopy.

Imaging or Making Pictures of the Sky

Up until the late 1800s astronomy was routinely performed strictly by looking through a telescope at the visible light emitted or reflected by celestial objects and recording what was seen with sketches or written descriptions. With the advent of photographic emulsions, experiments were expanded to include the recording of light not visible to the human eye, including infrared and ultraviolet wavelengths. Photographic techniques also made it possible for astronomers to start building an archive of images of the sky, to record and classify stellar spectra, and to compare new observations with old ones to look for small differences over time. It is no coincidence that the development of a stellar classification scheme and the rapid discovery of faint novas accompanied the application of photography to astronomy.

The next great advance in instrumentation came about with the development of electronic devices in the 1930s and 1940s. The first radio telescope was built in the early 1930s by Karl Jansky, who was working at Bell Labs, attempting to determine if naturally occurring static detected by radio receivers—and interfering with them—had a preferred direction. By recording the amount of detected radiation in different directions in the sky, Jansky produced the first image of the sky at radio wavelengths. Fundamentally, *imaging* is simply recording the amount, or intensity, of light from a given direction on the sky. Since the 1940s, astronomers have expanded their ability to image light across most of the electromagnetic spectrum.

Charge-Coupled Devices (CCD)

In the late 1970s advances in semiconductor technology allowed the manufacture of light-sensitive imaging detectors known as charge-coupled devices. They came into widespread use in astronomy during the 1980s, and recent advances have expanded their employment in commercial applications. The same detecting devices now found in consumer digital cameras and video cameras are located at the focal point of most of the world's research telescopes. The CCD is a grid of light-sensitive elements (called pixels), each of which records the detection of a photon by emitting an electron as a result of the photoelectric effect. The electrons that pile up in a given pixel are eventually "read out" of the CCD and recorded on a computer. Each pixel then has an electron count that is directly proportional to the number of photons that struck it.

The rapid advances that have occurred in CCD technology within the past 10 years have decreased their physical dimensions, improved their sensitivity, and lowered their noise (visual interference) characteristics. As fabrication techniques have improved, the typical size of a CCD has increased from 32 pixels on a side to 4,096 pixels on a side. The largest-format CCD cameras now employ several CCD chips aligned side by side to produce a larger detecting area. CCDs are supremely sensitive, currently producing an electron for each photon that strikes their surface. Early models were not this efficient, often losing electrons, thereby decreasing sensitivity.

The images CCDs produce can be immediately processed electronically and improved in quality. The main drawback of CCDs has been that they are relatively small and therefore cannot make wide-field images (which sample a large piece of the sky). The Hubble Space Telescope, for example, uses only four detectors (CCDs) in conjunction to produce images from its WF/PC2 and only samples a fraction of the total focal plane of the telescope. While the size of CCDs is a limitation, there is no alternative detector with equal sensitivity. The problem with CCDs generally is that they are small, and the area in a telescope's focal plane is large. As an example, Schmidt plates (the photographic plates that can cover about 95 percent of the focal plane of a typical Schmidt camera with a diameter of 0.5 m) are about 12 inches square. A fantastically large CCD is 1 inch on a side. A huge number of these large-format CCDs (about 144) would be required to cover the area of the focal plane. Take 144 (the number of CCD chips required) and multiply it by 4,096 × 4,096, and you get the number of pixels produced by a single snapshot. Limitations in the data transmission rates prohibited (at least at the time the HST was built) a fully sampled HST focal plane from making the design cut.

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Bolometer Arrays

Bolometer array technology first came into play during the mid- to late 1990s. This technology is only now being effectively transformed into working instruments on telescopes. Bolometers are electronic devices whose physical characteristics (most importantly their resistance) change in response to their temperature. Bolometers are typically made of amorphous semiconductor material. A small, measurable change in the current through a thermally isolated bolometer can be used to detect the energy of an absorbed photon. Large numbers of bolometers can be placed in arrays so that spatial (imaging) information can be measured in addition to spectral information. Their currently large physical size prohibits their use for very high spatial-resolution observations, but as the technology progresses, we can expect to see high spatial- and spectral- resolution data being generated by the next generation of bolometer arrays.

Bolometer arrays provide the added advantage of wide-field imaging and have already been used in astronomical applications, most notably the Submillimeter Common User Bolometer Array (SCUBA) system now operational on the James Clerk Maxwell Telescope (JCMT) on

Mauna Kea in Hawaii. SCUBA can image areas of the sky several minutes across and is designed to detect radiation from relatively cold celestial objects, such as distant, dusty galaxies. These objects typically emit most of their radiation in the far-infrared portion of the spectrum, where SCUBA performs best. We know little of this region of the spectrum, and the development of bolometers has led to new knowledge of the universe in this wavelength regime, opening a new spectral window on the universe.

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Radio Frequency Receivers

Radio telescopes are equipped with electronics to receive and amplify radio wavelength signals. Telescopes are composed of an antenna element and a receiver, known collectively as a "front-end," and an amplifier and signal-processor, together called a "back-end." The front-end systems on these telescopes are usually composed of some kind of horn-type antenna, which gathers the reflected radio light from the secondary reflector and guides it to a small amplifier. The amplified signal is then mixed with a local oscillator signal. The mixing process produces an intermediate frequency, which can be amplified and passed through filters to an integrator device or to a correlation receiver (for an interferometer). Different systems can perform the amplification and mixing process in a different order, but the result is the same: a signal, which is passed to some form of electronic integrator and then to a recording device.

Spectral line receivers can be formed by placing narrow-band intermediate frequency filter banks in the signal path, which produce summed signals for given regions of frequency space. Another type of receiver, called a correlation receiver, uses the interference properties of light to produce a signal, which can provide the intensity of the received radiation as a function of frequency. These receivers are used most often in modern telescope systems, although the filter bank technique still has a number of uses, especially for producing very high-resolution spectra with a minimum of complex electronics. The National Radio Astronomy Observatory, the Jet Propulsion Laboratory, and other international laboratories have been at the forefront of the development of radio receiver technology and electronics.

A new mixing device, called a "hot electron bolometer," is revolutionizing radio astronomy at high frequencies, near 1 teraHertz (THz). This quantum-mechanical device relies on the principle of resistance change caused by incident radiation absorption. When the absorbing element receives radiation, the device's temperature rises slightly, which causes a transition from a superconducting state (the detector is kept very cold) to a normal metallic state. During this transition, the resistance of the material changes dramatically. These devices are fabricated using nano-scale lithographic techniques. The absorbing element, a very thin strip of Niobium (Nb), is laid across a gap and connected to two gold metal pads. The strip is typically just 10 nm wide and about 100 nm long.

By either adjusting a bias current through the strip or varying the temperature of the strip, the resistance of the Nb strip is kept near the middle of the superconductor-to-conductor transition range. Incoming radio frequency radiation causes the electron temperature to be elevated slightly, increasing the resistance in a sensitive way. By injecting a signal of known frequency (called a local oscillator frequency) along with the signal of interest, the two signals interfere, or beat, causing the temperature of the Nb strip to fluctuate and therefore causing the resistance to fluctuate at the beat frequency. Since the voltage across the strip varies directly with the resistance, a simple measurement of the voltage produces a varying signal at a lower frequency, which can be amplified and passed to other electronic signal processing systems, as described earlier. The advantage of this type of device is the rather large range of frequencies (the bandwidth) it is sensitive to and its very low noise characteristics.

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Multiobject Spectrographs

Historically, spectrographs attached to telescopes gathered data through just a single slit. This technique allowed spectral data to be obtained from just a single object, while the light from other objects in the same field was not analyzed. In the 1980s and 1990s several techniques were developed that have eliminated this waste of valuable telescope time by allowing many objects to be analyzed simultaneously. They can be grouped under the title "multiobject spectroscopy."

The development of multiobject spectroscopy has culminated in the Sloan Digital Sky Survey, currently collecting data near Sunspot, New Mexico. This project consists of a telescope, imaging system, and multiobject spectrometer system. The imaging system is used to assemble a digital image of large portions of the sky and then select interesting objects for further spectroscopic analysis. The positions of the sources are used to machine aluminum "plug plates" where individual optical fibers feeding the light from up to 640 different objects to a spectrograph are attached, or "plugged." Up to nine plates will be used each night to record the spectra from more than 5,500 objects. The data are recorded digitally and processed automatically. This cutting-edge method of modern spectroscopy stands in stark contrast to individual sources being studied carefully by individual astronomers using data gathered on photographic plates, a method that was still in use as late as the 1980s. Smaller multiobject, fiber-fed spectrographs have been developed for many of the world's largest telescopes.

Recent developments in micromachining have made it possible to create a reconfigurable multiobject spectrograph. One such instrument is in use at the WIYN (Wisconsin, Indiana, Yale, and NOAO) telescope in Tucson, Arizona. The instrument is aptly called "Hydra" and consists of 100 optical fibers held in tiny armatures, which can be repositioned to within 40 arcseconds of each other. The ultimate device of this type is under development by a number of groups. One design involves an opaque material with a large number of tiny electronically controlled slits, about 200 mm by 2 mm in size, which can be placed in the focal plane of the telescope. Each slit will have an electronically controlled microshutter, which can be moved in increments as small as 10 microns. Such a design would allow spectra for most objects in the field to be obtained. Although still being developed, when this technology moves from the lab bench to the observatory, spectroscopy will receive another boost in efficiency.

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Planetary Exploration Technologies

NASA's planetary exploration missions utilize a variety of technologies that include transportation and mobility, sample acquisition and return, power, science instruments, and communications. NASA is involved in developing these technologies to explore and understand the other planets in the solar system. While astronomical understanding of the solar system has increased dramatically because of these missions, the astronomical detectors on these missions have historically not been at the cutting edge of astronomical technology. The reason for this is that to be included in a space mission the technology must be well proven on Earth, then sent to a distant planet. However, even with older technologies, discoveries have been made or enhanced using advanced techniques. A perfect example can be found with the Hubble Space Telescope. Pictures taken with the telescope are limited in the resolution they can provide by the size of the pixels on the CCD detectors. Researchers found that when the telescope would take multiple images of the same object, it would not always focus the same light on the exact same detector—a slight shift would be present. By combining the images using a technique called "drizzling," a higher-resolution image could be created by accounting for the sub-pixel-sized shifts that occur between image acquisitions. Similar techniques, combined with cutting-edge technology, have allowed NASA to continue to produce stunning scientific results.

The tradition of using only well-known technologies has changed with NASA's introduction of "Faster, Better, Cheaper" space probes. The "Faster, Better Cheaper" concept is the brainchild of Dan Goldin, the former NASA administrator, who realized that NASA engineers and scientists were avoiding the possibility of mission failures by overdesigning NASA satellites. This overdesigning included multiple redundant systems, proven (and therefore old) technology, and limited cutting-edge instrumentation. Through overdesign, both costs and the length of time necessary for mission readiness increase. The "Faster, Better, Cheaper" method allows NASA engineers to risk failure by using more recent technologies, reducing costs by eliminating multiple redundant systems, and speeding up mission development time by streamlining the design, engineering, and construction processes. Although some failures have indeed occurred, notably two high-profile missions to Mars (Mars Polar Lander and Mars Climate Orbiter), the "Faster, Better, Cheaper" methodology has produced dramatic successes. One of these was the Mars Pathfinder mission with its rover Mars Sojourner. This mission employed a landing mechanism novel to NASA—large inflated bags that allowed the probe to bounce safely to rest—as well as advanced technology instruments such as CCD cameras such as those found in video cameras. After the loss of the two high-profile Mars missions, a congressional investigation and an internal NASA review panel placed some constraints on just how far "Faster, Better, Cheaper" could be expanded. These reviews advocated more system checks to reduce the likelihood of future failures, but they continued to advocate the use of cutting-edge technology and streamlined missions instead of a return to the behemoth multiple redundant missions of the past such as the Mars Viking landers.

Even with the implementation of "Faster, Better, Cheaper," mission development and travel times can result in outdated technologies arriving at a solar system object. Of course, these instruments have the huge advantage (in resolution) of being far closer to the planet or surface that they are imaging. For example, the stunning surface images of Mars made with the Mars Global Surveyor imaging camera benefit from the fact that the camera is orbiting the planet and is not located at a distance nearly half the way to the sun (as are all telescopes on Earth). The cameras on this mission are able to resolve objects as small as a few meters in size and were built from spare parts intended for a previously launched (and lost) mission, Mars Observer. Many of the remote sensing, launch and reentry, and robotic techniques that need to be employed in these missions are on the cutting edge of the fields of aeronautics, communications, and robotics.

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Notes

1. The largest radio telescope, Arecibo, is not steerable but is stationary in a valley in Puerto Rico. See "Telescopes" below.

2. Angular resolution for ground-based optical telescopes is typically measured in arcseconds, or 1/3,600 of a degree. Longer wavelength telescopes often give their resolution in larger units, like arcminutes or degrees. Ground-based optical telescopes can rarely achieve better than 1″ resolution without the use of adaptive optics systems.

3. Many objects are best observable from one hemisphere or another. For example, the center of our galaxy, the Milky Way, is best observed from the Southern Hemisphere.

Chapter Three

Astronomy and Society

When asked to comment on the interplay between astronomy and society, many people might pick examples related to a dominant post–World War II phenomenon: the space race. The United States and the Soviet Union spent considerable time and money trying to beat one another to significant milestones in space: the first satellite to orbit the Earth, the first animal to live in space, the first man or woman to orbit the Earth, the first person to land on the moon. While these milestones represent profound technical achievements, they have relatively little to do with astronomy. Certainly, the technology associated with getting humans into orbit has also gotten instruments like the Hubble Space Telescope into orbit, but the same technology has gotten communications satellites and spy satellites into orbit as well. No one believes, of course, that these latter technologies were developed for astronomers. Astronomical discovery has also been used to justify projects like the Apollo missions to the moon. In fact, lunar rock samples have added greatly to our knowledge of how the solar system and, in particular, the Earth-moon system formed, but, again, few would argue that the recovery of moon rocks was the primary reason that we sent humans to the moon.

So if modern astronomy is not about sending rockets into space, what is it about? Primarily, it is about understanding: understanding how the universe came into being, what its rules are, and how those rules make the universe work in ways we can observe. These are not issues that affect most people on a daily basis—certainly not in the ways that disease, stock market fluctuations, the unemployment rate, and weather patterns do. And yet observations related to astronomy have been made for thousands of years. Humans have kept track of the relative motions of the planets, sun, and moon since ancient times. People, it seems, have always looked at the night sky and wondered why things are just so. And as humans have populated the Earth, they have sent enough light into the night sky to make the Milky Way, for example, impossible for most of the world's population to see. Light that travels upward is called "light pollution," and like its companion plague air pollution, it is a topic that is positioned squarely at the interface between science and society.

THE QUESTIONS THAT ASTRONOMY ASKS

As a discipline, astronomy does not impact society in the obvious ways that chemistry (pharmaceuticals), biology (ethics of genetic engineering), or computer science (the Internet) do. Yet astronomy is one of humanity's oldest scientific disciplines. Some of the earliest written records are the writings of Babylonian astronomer-priests recording the motions of the planets with respect to the background stars. These early efforts were made by societies that did not have large amounts of leisure time, so clearly there must have been some social usefulness to such astronomical observations. In what ways was astronomy useful to society in those ancient times, say, in Babylon, circa 1000 B.C.E.? One obvious answer is that the heavens were remarkably good keepers of time, and they reflected the seasonal cycles that were of the utmost importance to agricultural societies. Much as the U.S. Naval Observatory keeps the official time for the nation today, synchronizing the Internet, business transactions, and some other aspects of day-to-day life, so too did ancient astronomer-priests keep time for their societies, predicting seasonal change, establishing festival dates, and advising leaders of auspicious times to begin military campaigns.

Archaeoastronomy is the study of the astronomical efforts of ancient peoples as evidenced by alignments at archaeological sites and anthropological studies of the people who lived at or near such sites. This endeavor has shown us that early societies were clearly aware of events like the summer and winter solstices, fall and spring equinoxes, and the cyclical motions of the planets and the moon. For both practical and ceremonial reasons, this form of timekeeping was important. One practical reason was to know when during the year to plant and harvest crops. The ceremonial reasons may have been to anticipate (as is clear from some archaeological sites) and celebrate such events as the end of the sun's dipping low in the sky and the start of its ascent to its greatest height in late June at the summer solstice.

Alignments of stones from Europe to the Americas show clearly that societies kept track and cared about the positions and motions of the sun. It would have been easy for a careful observer to note, for example, that in the course of a year the sun sets farther and farther to the south each day as the winter months approach. It then appears to stand still on the winter solstice and move to the north each day until about June 21, when it stands still and begins its motion to the south once again.

The first day of each lunar month was fixed by the first observation of the new moon. It is possible that the regular observation of the bright moon and its phases—which fixed months for purposes of business and government—led to early astronomers noticing other regular motions. The Sumerians invented cuneiform script, and some of the earliest written records of astronomy are found in this form. Texts survive from the time of the first Babylonian dynasty (c. 2000 B.C.E.) recording the positions of the sun and moon, names of constellations, and the position of the planet Venus with respect to the stars. Observations like these made by early societies and the pseudoscientific inferences derived from them are the origin of astrology. While most people today dismiss astrology as mere superstition, the presence of horoscopes in daily newspapers attests to the fact that many of us still find comfort in the fantasy that the future can be predicted by the configuration of the heavens. In fact, one might argue that astrology impacts the daily life of more people on the Earth than astronomy.

The keeping of the calendar by means of astronomical observations was clearly of use to early societies. By about 1000 B.C.E., astronomical observations reveal a deeper concern with astrology, interpreting the positions of the planets and stars to predict the future. By this time, astronomers had clearly noticed the relative movements of the moon, stars, and bright planets, and they were chronicling them. There is also evidence that, by about 800 B.C.E., astrologers had noticed the regularity of lunar eclipses and were able to predict them. Late Babylonian texts further indicate an ability to predict solar eclipses, which means that astronomers were accumulating data over periods of many years and looking for patterns in the data. While many of the conclusions that these ancient observers drew were astrological, their observations and techniques were often the products of sound scientific method. By 1000 B.C.E., Chinese astronomers were keeping careful records of the daily motion of the stars and such transient phenomena as comets.

Until the advent of the Greek philosophers, all astronomical efforts that we know about were confined to a priestly class. As J.L.E. Dreyer comments, "[S]peculations on the origin and construction of the world were always interwoven with mythological fancies to the exclusion of independent thought. Astronomy may be said to have sprung from Babylon, but cosmology . . . dates only from Greece." Trade and conquest at the time of Alexander brought the Greek people into contact with those farther to the east, where astronomy and astrology had developed greatly in the previous two millennia. Greek astronomers began to move beyond record keeping and soothsaying to taking a measure of the world around them. Thales of Miletus (624–547 B.C.E.) apparently predicted a solar eclipse in 584 B.C.E. The Greek astronomer Aristarchus (310–230 B.C.E.) first suggested that the Earth was not at the center of the universe but that it orbited the sun and rotated on its axis. The daily motion of the sun and stars, then, were the result of the Earth's motion through space. So out of keeping with everyday experience was this suggestion, however, that it was not until the time of Nicolaus Copernicus (1473–1543), 1,700 years later, that the heliocentric idea became widely accepted. The writings of Copernicus began a revolution in our concept of where we fit into the universe, which proceeded through the work of Johannes Kepler (1571–1630), Galileo Galilei (1564–1642), and finally Isaac Newton (1642–1727). Newton's conception of the mechanics of the universe remained basically unchallenged until the twentieth century.

Greek astronomers were apparently the first people to have suggested that the Earth was not flat, as it appears to be on local scales, but spherical. The astronomer Eratosthenes (c. 250 B.C.E.) performed a simple but ingenious experiment, which not only showed that the surface of the Earth is curved but also yielded an accurate measurement of its circumference. When Eratosthenes made his estimate of the size of the Earth, he placed humans on the surface of a very large sphere, around which (apparently) the entire universe revolved. Suddenly, the world over which humans had dominion was a much larger place, its local flatness an illusion caused by our tiny size. Were we large enough, the curvature of the Earth would have been obvious all along. It is not clear, though, that Eratosthenes's conclusions reached a wide audience. In fact, we only know of his work because of references in later scientific and philosophical texts.

Early societies were surely more concerned with when to plant the crops than with the observation that the Earth was an enormous sphere. Much of the knowledge of the natural world put forth by

Greek astronomers and mathematicians was set aside until it was rediscovered in Europe during the Renaissance.

We know far more about the personalities of more recent astronomers and scientists than we do about their ancient counterparts. Isaac Newton, for example, was notoriously antisocial, and many great astronomers through time seem to have had little patience for the societies in which they lived. Astronomers tend to keep strange hours, staying up all night either to make their observations (at least, such is the case with optical astronomers) or to make sense of their data. Yet it is impossible to ignore that, since the earliest historical times, in addition to keeping the calendar, reading the future, and measuring the extent of the world we inhabit and of the universe, astronomers have been looking for answers to some of the most fundamental questions that humans ask. And recently, astronomers have been rather successful at finding observationally based answers to many of these questions. Some of the fundamental questions that face science and society today may eventually be answered by observations yet to be made by astronomers in coming centuries.

What are some of the questions, how have astronomers addressed them, and how might they continue to approach them in the future?

Why are we here and how did we get here? One might argue that some of the first people to make systematic observations of the night sky and record them, the astrologers, were looking for answers to this question. The question of the purpose of existence is perhaps as old as the consciousness of existence itself. While there are many levels to this question, astronomy has laid out a fairly detailed explanation of why we are here or, perhaps more accurately, how we got here. In the fullest sense, the question of *why* may not be a question for astronomers at all but for theologians and philosophers.

How long have we got? It is only natural to wonder how long we as a species will survive, and predictions that the world is coming to an end are surely older than astronomy. Astronomers have explored this question on many levels, from the lifetime of the Earth to that of the sun and even the lifetime of the universe. Astronomers are also deeply involved in the ongoing effort to track the orbits of potentially dangerous asteroids.

Are we unique? The Chinese have long referred to their land as the Middle Kingdom, and it is understandable that we all tend to think of our own location as the center of it all. Some of the most dramatic shifts in our understanding of exactly where we are located (in the solar system, in the galaxy, in the universe) have come about as a result of careful observations by astronomers.

Are we alone? One of the most frequent connections between astronomy and society comes from this fundamental question. From the profound discoveries of planets orbiting other stars to the ludicrous tabloid headlines seen at the grocery store checkout line, this topic—more than any other—garners attention from people who, otherwise, would not give astronomy a second thought.

We now turn to each of these questions in more detail and explore the ways in which astronomy forges connections to society by addressing some of its most fundamental questions.

Why Are We Here?

The earliest explanations of why we are here come from the creation stories of the world's great religions. According to the Judeo-Christian tradition, the world was created in six days. Many creation stories address a fundamental point, which is that there might have been a beginning to time, and if there was a beginning, then just how was the start button pushed? Is a beginning itself evidence of divine intervention, or did the universe come into being spontaneously?

Astronomy today can, for the most part, explain how we came into being. Starting with the Big Bang, through the origin of the matter that now exists in the universe, through the origin of galaxies, stars, planets, and the conditions necessary for life to arise, the evolution of the universe from the earliest times is quite well understood. There are, of course, many unanswered questions and details still to be worked out (see Chapter 6), but humans have made remarkable progress, especially in the past century, in their understanding of the fundamental chronology of the evolution of the universe from the moment it began. And some physicists, like Victor Stenger, make the case that the origin of the universe itself can be explained scientifically, through quantum fluctuations, without any need for the hand of a creator. The question of "design" in the universe is an issue at the boundary between science and religion. In a recent lecture at Agnes Scott College in Decatur, Georgia, particle physicist and Anglican priest Sir John Polkinghorne described the current state of dialogue between science and religion.

He used the analogy of a front in a battle between two opposing forces and proposed that there were regions along the front where battles rage fiercely (biology and religion) and regions where the forces have been more peaceful (physics and religion). Polkinghorne argues forcefully for the case of design in the universe, for the hand of a creator, but most scientists are very uncomfortable with intermixing science and religion. In the last decade, there has been a bit more openness among scientists to put down their thoughts about this previously forbidden topic. The fact that a highly regarded physicist such as Paul Davies would write a book titled *The Mind of God: The Scientific Basis for a Rational World* (1992) implies that there is a change in the willingness of at least some scientists to take on more metaphysical topics.

A large piece of the puzzle that still remains elusive is the origin of life in the universe. While astronomers can claim with some certainty that the conditions necessary for life are probably quite common in the universe, it is still unclear how matter (given the right conditions) is able to organize itself in such a way as to become living. Paul Davies outlines the fundamentals of the problem in his recent book *The Fifth Miracle* (1999), and David Darling gives a broad overview of the topic in *Life Everywhere* (2001). One of the marvelous and unique aspects of life is that it contains within itself substances, DNA (deoxyribonucleic acid) and RNA (ribonucleic acid), that carry the information necessary to reproduce more of itself from raw materials. Life, as Davies puts it, is a complex mix of hardware and software. If humans can develop self-replicating automata, machines that can build more of themselves from raw materials, will they be called "alive"? This topic may seem to wander far afield from the issue of astronomy and society, but as all of these recent books as well as recent research articles make clear, the origin and evolution of life on the Earth cannot be disentangled from the details of the early solar system. If astronomical investigations will eventually give us a clear model for how the early solar system evolved, then it is also astronomy that will explore some of the boundaries that are the preconditions for life.

We already know from radio telescope observations that the raw materials for life, complex hydrocarbon molecules similar to those found in automobile exhaust, are distributed throughout interstellar space. The question is: How did the first living thing come into being? Did it originate on the Earth? Was the Earth seeded with living material from another planet in the solar system? These are questions that are mostly in the domain of molecular biology, but astronomy soon will be able to tell us, for example, whether life existed, or exists, on Mars, or whether it existed or exists on Europa, an ice-and-water-enshrouded moon of Jupiter. And if life did or does exist in these places, does it have the same blueprints (DNA) as life here on the Earth? Some of the most ambitious and exciting space missions planned in the coming decades will attempt to answer these questions about the origin of life and its prevalence in the universe (see Chapter 2).

Perhaps *we* are the *why*. Not necessarily we as humans but simply we as observers of the universe. Perhaps consciousness and observation are one of the end results of the existence of the universe. Regardless of what one thinks about the prospect for life in the universe—and there are few who would argue that simple life, bacteria, for example, are unique to the Earth—complex life cannot appear early in the history of the universe. Complex life, whether it is rare or abundant, takes time to evolve, and self-consciousness has developed in at least one corner of the galaxy. If it has occurred here, many argue that it must have occurred elsewhere. But regardless of how widespread it may be, self-consciousness, and the ability and the desire to figure out the "rules" that govern the universe that we inhabit, does not come along with bacterial life. It appears to have come along with this oversized brain that we developed as a species, so large that we are born as helpless appendages to our oversized heads.

Does the universe exist if no one is there to observe it? Perhaps the answer to why we are here is simply to be observers, to study the universe from its largest to its tiniest scales and to understand it—and, as we understand it, to come to appreciate and understand our own origins.

How Long Have We Got?

One of the vexing problems of nineteenth-century astronomy was how the sun could have been producing energy at its current rate for enough time to account for the apparent geological age of the Earth. The problem is that if the sun were producing energy by chemical means—that is, oxidation or burning—then it should burn for only a few thousand years. Although the biblical literalists might have been happy to hear of the Earth's youth, there was a clear problem for scientists. It was soon calculated that even if the gravitational contraction that the sun is experiencing were to account for its luminosity, it would only shine for perhaps 100 million years. Geologists later determined through analysis of radioactive materials in rocks that the Earth was apparently many times older than this. Some form of energy production had to be discovered that would allow the sun to produce energy at a prodigious rate not for thousands or even tens of thousands of years but for billions of years.

When an instructor tells students in introductory astronomy that the sun will eventually swell to the size of the orbit of Mercury and that the Earth's oceans will be vaporized, leaving behind a rocky chunk resembling the Earth when it just formed, the class typically gets a bit concerned. A kind-hearted instructor will go on to tell the students that this dire event will not occur for several billion more years. How do astronomers know this? How do we know how long the sun and the planets that orbit it have got?

It turns out that the energy source that accounts for the sun's energy production over billions of years is nuclear fusion, primarily the fusing of hydrogen into helium at its core. When the sun begins to run low on nuclear fuel, it starts to use hydrogen farther from its core (Figure 3.1). The sun's outer layers then heat up from the locally generated energy, and the sun swells. This dying, or *red giant*, phase of a star's life is not, of course, unique to the sun. Most stars apparently go through such a phase. The familiar reddish star Betelgeuse in the constellation Orion is an example of a red supergiant. Betelgeuse is so large that astronomers have recently been able to resolve its disk with the Hubble Space Telescope and with the Very Large Array (see Chapter 2).

Many first-time telescope users, either amateurs or students in an introductory astronomy class, are disappointed when they first learn that stars don't look appreciably different through a telescope than they do with the unaided eye. All stars (aside from the sun) are so far away that even in a telescope they appear as nothing more than points of light. Of course, stars are brighter when viewed through a telescope (because the surface area of a telescope's mirror is larger than the diameter of the human eye), and one can also see faint stars invisible to the naked eye, but distant stars do not reveal any surface detail, except for giant Betelgeuse.

In terms of the life of the sun, we have a few billion more years. What will be around on the Earth in a few billion years? Who knows? Most politicians are a bit too concerned with short-term concerns to give the eventual fate of the sun much thought. The length of the life of the sun is not, then, something that will immediately impact society. However, variations in the sun's brightness that occur over long periods may significantly affect the surface temperature and atmosphere of the Earth in ways much more significant than human-produced pollutants. But the thought of the Earth's eventual fate—to return to

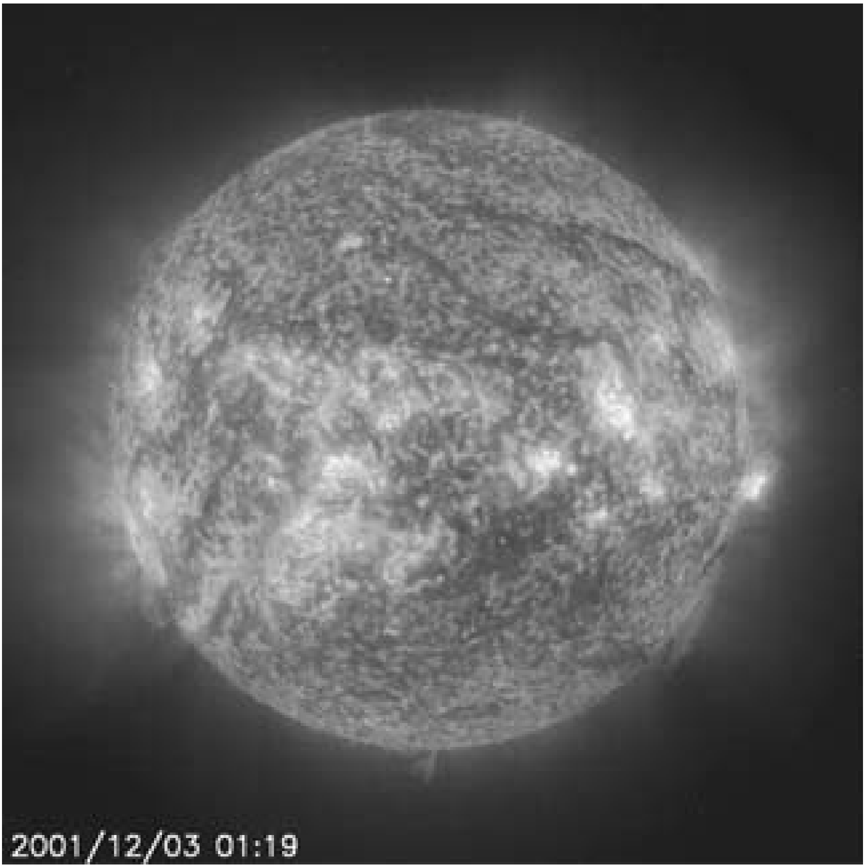

Figure 3.1. This image of the sun is from the Solar and Heliospheric Observatory (SOHO) Extreme Ultraviolet Imaging Telescope (EIT) at 304 angstroms, which operates continuously in space. The EIT-304 instrument is most sensitive to material in the sun's atmosphere that is 60,000 to 80,000 degrees Kelvin. SOHO is a project of international cooperation between the European Space Agency (ESA) and NASA. Courtesy of the Solar and Heliospheric Observatory and the EIT Consortium.

a waterless, rocky lifeless world—does have an impact on us all. This knowledge should make us mindful of the fragility of the world we inhabit and the enormous degree to which we are dependent on the details of the evolution of our host star.

Of more immediate concern to most people are asteroid and comet impacts. This area appears to be one in which the immediate, practical value of astronomical observations is straightforward and clear. Students are often surprised to find that asteroid discovery and tracking programs, while they do exist, are not given higher priority by the world's governments. And these thoughts are not simply based on doomsday movies like *Deep Impact* and *Armageddon* but appear to be founded on a sincere concern for safeguarding the planet and for using astronomy in a way that would clearly be beneficial now and to future generations.

Asteroid impacts like the one that hit Tunguska, Siberia, in 1908 are not rare events. Based on the cratering histories of the Earth and the moon, impacts of its magnitude take place on average every 100 years. If the object that caused the event in Siberia almost 100 years ago were to strike the Earth near a large city, the effect would be catastrophic. Astronomers would have some explaining to do if they failed to predict such an event, and yet on the scale of planetary systems, such impacts are incidental.

While astronomers have moved away from their astrological roots, one popular image of the astronomer as predictor of the future has remained. Today, people do not look to astronomers to foretell the fate of royalty or the outcome of battles, but they do expect them to warn of incoming asteroids. News stories that describe upcoming close encounters with recently discovered asteroids surface periodically. What would we do if we were to discover an asteroid on a collision course with the Earth? Depending on how much time we had, we might just wait for the inevitable, or we might try to develop the technology to avert disaster. Either way, the impact on society would be enormous—and, perhaps, all too literal.

NASA has committed resources to the discovery and tracking of asteroids that might pose a danger to the Earth. Near Earth Asteroid Tracking (NEAT) has become a priority, partially as a result of increased citizen awareness about the risks facing the planet. NASA's NEAT consists of telescopes located at two sites, one at Maui Space Surveillance Site (NEAT/MSSS) and the other at Palomar Observatory (NEAT/Palomar). Both sites have 1.2-m-diameter telescopes that are involved in robotic searches (also called autonomous tracking) for asteroids that have trajectories that might pose a danger to the Earth. The telescopes have already produced important scientific results, one of which is indeed the reduction in the estimate of the number of large (diameter greater than 1 km) near-earth asteroids. What had been thought to be 1,000 to 2,000 objects is now thought to be more like

500 to 1,000. NEAT/MSSS has been active since 2000, and NEAT/Palomar since 1999. NASA has spent nearly half a million dollars in the retrofitting of the Palomar telescope, and CalTech has provided the facility. The goal of these observations is to discover 90 percent of the 1-km- and larger-sized asteroids near the Earth within 10 years. In August 2001 alone, NEAT discovered 17 near-Earth asteroids including 2 larger in diameter than 1 km and 4 that might actually pose a danger to the Earth.

But questions of our eventual fate need not be limited to this little corner of the universe. The question of our collective destiny can be asked on the largest scales as well. How old is the universe, and what will be its eventual fate? In the 1920s, Edwin Hubble first proposed that the universe was expanding as the result of an original explosion of space itself, which brought the universe into being: the Big Bang. The famous Hubble Law, derived from observing a paltry few galaxies, describes the direct proportionality between the distance to a particular galaxy and the measured Doppler shift of its recessional velocity into the red part of the spectrum. What this relationship showed Hubble was that, on large enough distance scales, every galaxy was rushing away from every other galaxy. This relationship has been confirmed over much larger distance scales, and evidence for the original explosion that brought the universe into being and fueled the expansion has been discovered. The CMB, or cosmic microwave background radiation, was predicted in the 1940s and then discovered in the 1960s. It is the long-wavelength radiation that fills all space as the lingering echo of the Big Bang. One of the most fundamental remaining questions is, What will eventually happen to the expansion? Will the universe lose the battle against gravity and collapse in a Big Crunch, or will the expansion continue forever, with galaxies redshifting away from one another to eternity?

Current research by astronomers around the world into the nature of high redshift, Type Ia supernovae, explores this very issue. The conclusion suggested by the early data from two independent groups is that the universe is not only expanding but also accelerating in its expansion. The work of the groups researching this phenomenon is described in more detail in Chapter 1.

Are We Unique?

As is apparent to any observer of the night skies, the sun, moon, planets, and stars all orbit around the Earth. They rise in the East and set in the West day after day. We stand unmoving on a solid Earth watching the night sky go wheeling past. To a careful observer, a geocentric theory of the universe is not such a silly idea. When one watches the night sky, it is easy to see why for so long astronomers modeled the universe in such a way that the Earth was located at the center.

The problem (for astronomers) is that this Earth-centered, or geocentric, theory could not, in the end, properly describe the motions of the planets. While it was a reasonable predictor of planetary motions for several thousand years, the original description by Aristotle and Ptolemy had to be modified over time to keep the geocentric model consistent with the observed motions of the planets. It was careful astronomical observations that brought down the Ptolemaic model and, along with it, a worldview in which human beings and the Earth were in a central, privileged position. Copernicus proposed a heliocentric view of the universe—apparently after reading about the theories of the Greek astronomer Aristarchus—in which the planets traveled around a stationary sun in circular paths. The scientific problem with Copernicus's theory, which likewise proposed circular planetary orbits, is that while it was perhaps more satisfying philosophically and more simple in concept, it was no better a predictor of planetary positions than a modified Ptolemaic model.

In the end, Johannes Kepler, using some fine observational data from the Uraniborg Observatory of Tycho Brahe, determined that the heliocentric theory would work if the planets moved not in perfect circles but in ellipses. Thus, the Earth was moved from its central position to simply being the third planet orbiting the sun. It is hard to imagine the psychological shift that this proposal would have caused at the time. It was perhaps as significant as the unambiguous discovery of extraterrestrial life might be today. We live in an age when we are accustomed to the news that our planet, our star, and even our galaxy are not all that special, that there are billions of stars just like the sun, and that there are likely planets around many of them. Recent discoveries by Geoff Marcy (UC Berkeley) and others have shown us that planets clearly orbit distant stars (see Chapter 1). The nineteenth and twentieth centuries only pushed us farther from a central place. Immanuel Kant first suggested that the spiral nebulae that had been observed with the largest telescopes were in fact "island universes" and that our galaxy was just one of these islands in the vast cosmos. Harlow Shapley (1885–1972) showed in the early part of the twentieth century that our sun was not at the center of our galaxy but (based on the positions of globular clusters) was on its outskirts. And we now know that the sun is located on a material spur between two spiral arms in the galaxy.

On the face of it, the news that came back from Edwin Hubble in the 1920s must have been promising to those who wanted the Earth to have a special place. While the Earth was not at the center of the solar system, and the sun was not at the center of the galaxy, it appeared that all the galaxies in the universe were rushing away from *us*, the light from their stars shifted into the red part of the spectrum. Unfortunately, the observation that all galaxies were rushing away from us did *not* mean that we were at the center of the universe but simply that the expansion of the universe would look the same to all observers. This phenomenon is sometimes referred to as the *cosmological principle*. That is, an observer anywhere in the universe should see all other galaxies (sufficiently distant so that they are not part of a local concentration of galaxies) moving away from him/herself. Imagine dots drawn on the surface of a balloon. As the balloon is inflated, all of the dots move away from one another, and from the point of view of any one dot, all of the other dots are moving away (no matter which dot you pick). In this analogy the dots are galaxies, and the surface of the balloon represents, albeit imperfectly, the expanding universe.

Modern astronomers have tended not to interpret these discoveries philosophically (certainly not in their scientific writing) but simply to present them. More philosophical reflection is displaced into popular-level books, like the many that Paul Davies and others have written. We appear to be rather ordinary in the universe in every way. Should that make us feel insignificant? Or should it make us feel strangely hopeful? If we are rather ordinary, and we are here in the universe, perhaps we are not alone. The last few years have made it increasingly obvious that we are not the only planet orbiting a star. At last count, over 60 planets had been discovered orbiting solar-type stars, and most recently, one of these planets passed between us and its host star, causing the host star's light to dim. This passage was a confirmation of the presence of a planet discovered by the Doppler shift method, described in Chapter 1.

So we are rather ordinary; other stars are clearly out there, other planets are out there, and we are not at the center of anything. The question that many people ask of astronomers is this: Is there other life out there on those distant planets? The answer to the question (so far) is that we do not know. Of any question that astronomers may answer in coming years, this one may well have the greatest social impact.

While it has been clear for quite some time that the Earth is not at the center of anything, the question of Earth's uniqueness in other ways remains viable. In their recent book *Rare Earth* (2000), Peter Ward and Donald Brownlee explore the Earth's uniqueness on other grounds. Many astronomers, like *Life Everywhere* author David Darling, have dismissed their arguments as modern geocentrism, implying that given the number of possible planetary systems in the universe, we cannot possibly be unique. But Ward and Brownlee carefully present a series of scientific arguments to make a persuasive case that it may not be as simple as others have proposed for a life-sustaining planetary system to evolve. As always in science, their proposals have observational tests and will be proved or disproved by experiment. But the point is that the question of the uniqueness of our planet is not just ancient history. It is still a present concern.

Are We Alone?

Most astronomers believe firmly that as far as complex life goes, we are alone in the solar system. There may or may not be bacterial life in the subsurface oceans of the moons of Jupiter or deep in the rocks of Mars; we simply do not yet have enough observational evidence to tell one way or the other. Europa, one of the four large moons of Jupiter, is one possible location in the solar system where life might have a chance, and recent discussions have centered on the energy that would be available to microbial life. The Galileo mission that flew to Jupiter and its moons has confirmed that the cracked icy surface of Europa suggests that there might be a significant layer of water beneath its crust. Future missions to Europa may be able to determine if any life exists in a subsurface ocean there. The work of astronomers and biologists is beginning to overlap in the studies of life in extreme environments.

The latest studies of our own planet indicate that life may well have originated beneath the surface of primeval oceans or beneath the surface of the Earth. Life at the surface of a planet, so familiar to us, may be an anomaly. The more we learn about other planets and moons, the more we are able to reflect upon the origin of life on our own planet.

As discussed in Chapter 1, some researchers take the approach that the best way to find out if we are alone is not to study the survivability of extreme environments but to look for radio transmissions from other civilizations. The largest of these projects, SETI, the Search for Extraterrestrial Intelligence, is an organized and privately funded effort to scan the radio spectrum for the presence of broadcast signals from other civilizations. The mission of SETI was discussed in more detail in Chapter 1, but it is important to restate here that SETI is currently supported only by private funds. It appears that in terms of broad support from citizens the search for planetary environments is more appealing than the search for extraterrestrial signals. Perhaps this is because the search for planets and the investigations of the origin of life have fewer preconceptions. To scan the skies at particular frequencies for signals of extraterrestrial origin seems to many to be based on too many assumptions about the desire and willingness of any other life to communicate with us. Though we would rather not ponder it most of the time, it is possible that other life in the universe might take little more notice of us than we would of mold growing on cheese in the refrigerator. However, it seems that the two approaches to look for life elsewhere are complementary. Certainly once technology has developed to the stage where we can identify other Earth-like planets orbiting sunlike stars, the scientists involved with SETI will surely want to point their sensitive radio telescopes there.

Astronomical observations have been at the root of some of the major shifts in our understanding of our place in the scheme of things. We live on a large sphere, our location and star are rather ordinary in the universe, and while the specifics of our planetary system may be unusual, we are not in any way centrally located. Moreover, one of the system's most permanent features and the source of life, the sun, will burn out in about 4.5 billion years. But while we appear to be ordinary, we have—despite great effort—detected no other life, either in the solar system or beyond it. When and if we do receive definitive evidence that life exists elsewhere, astronomers (or perhaps astrobiologists) may be the ones calling the press conference.

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A FEW PRACTICAL ASIDES

Solar Activity and the Earth

Perceived astronomical threats to the Earth are not a recent development. Since ancient times, many cultures have seen comets as heralds of doom and have feared that certain planetary alignments would bring about great changes here on Earth. These types of threats have been as popular as ever in recent years, perhaps amplified by the millennial fever that recently passed. From the dire results of planetary alignments to the Earth-snuffing ability of even modest-sized asteroids, our fear of things we cannot control in the sky is palpable. However, large asteroids are relatively rare, and planetary alignments appear to have (at most) a psychological effect.

The variablity in solar activity, however, occurs over relatively short timescales and can cause real headaches for our technological society. Longer timescale variations in solar activity may have dramatic effects on the atmosphere of the Earth, so necessary for our survival. Our growing understanding of solar activity, its causes and its impact on the Earth's environment, is one of the great achievements of the twentieth century.

At solar maximum (which occurs every 11 years), large numbers of sunspots are seen, and the number of solar flares increases markedly. Coronal mass ejections (CMEs) are known to occur around the time of solar maximum and are associated with large changes in the magnetic field at the surface of the sun. Most of these ejections (which can occur daily) "miss" the Earth, but if CMEs intersect the Earth's orbital path, they may cause satellite communication failures. Occasionally, induced electric currents in Earth-based electrical transmission systems or pipeline networks can damage infrastructure.

So real and important are the effects of the sun's activity on the Earth that government agencies publish daily space weather outlooks. Below is a Space Weather Outlook for April 6, 2000:

SEC Space Weather Advisory

Official Space Weather Advisory Issued by NOAA Space Environment Center Boulder, Colorado, USA

SPACE WEATHER BULLETIN #00-2

2000 April 06 at 02:50 p.m. MDT (2000 April 06 2050 UT)

GEOMAGNETIC STORM BEGINNING

The ACE spacecraft, located approximately one million miles towards the Sun, detected a fast-moving ejection in the solar wind at approximately 10:00 AM MDT today (1600 UT on April 6). This structure is believed to have been launched from the Sun late on April 4. The Earth's magnetic field responded shortly thereafter, and major storm conditions are now occurring at all latitudes.

It is expected that this storm will continue for the next 24–36 hours. Significant impacts on terrestrial systems include some electrical power systems, spacecraft operations, and communications and navigation systems.

In terms of the New NOAA Space Weather Scales, this storm may reach category G3 (strong) level.

Perhaps the best-known example of such an outage was experienced at the last solar maximum in eastern Canada. In early March 1989, a "geomagnetic storm" disabled the entire Hydro Quebec system, an electrical power grid that serves more than 6 million customers. At the dawn of the new millennium, we are at another solar maximum and need to understand that our technological society is still at the mercies of the cyclical nature of the sun's activity.

The Environmental Impact of Observatories

Astronomy's impact on society goes beyond philosophical reflections upon our place in the universe, of course. Today's observatories, whether located in orbit or at the highest altitudes on the Earth, have an impact on our environment. Since state-of-the-art telescopes require dark skies, high altitudes, and dry climates, Earth-bound astronomical observatories are located in some of the most otherwise undisturbed environments on the planet. As a result, there have been periodic clashes between astronomers and environmentalists.

One classic example is the battle involving how construction of telescopes on Mount Graham would affect the indigenous red squirrel population. The Arizona-Idaho Conservation Act (AICA) of 1988 gave the University of Arizona (UA) the right to build three telescopes and an access road on Mount Graham. The act also stipulated that if a U.S. Fish and Wildlife Service (USFWS) study showed no significant negative impact on populations of the endangered Mount Graham red squirrel, the university could build up to four more telescopes on the site. The Sierra Club Legal Defense Fund sued the USFWS and UA in 1989 to halt construction of the observatory. When, in 1990, a ruling came down on the side of the USFWS, the Sierra Club appealed the decision. The decision was upheld, and a second group sued the USFWS and the UA in 1991. By 1994 the issue had been resolved, and the observatory was under construction.

In the end, construction of the observatory appears to have had no negative impact on the red squirrel population, which has increased markedly since construction began in 1989. Evidence now shows that the squirrel population responds much more drastically to the amount of rainfall in the Southwest and that the original low population numbers were due to an extended period of low rainfall in the Mount Graham ecosystem. Despite this finding, there are independent reports that the squirrel population decreased in the past year. Whether this decrease marks the beginning of a downward trend will not be clear until more time has passed.

These types of conflicts are particularly painful to astronomers, many of whom are committed environmentalists, hikers, and lovers of the outdoors. But this type of conflict is becoming more common, especially when construction sites are in the United States. New observatories built in Chile and other South American countries often face fewer environmental challenges than the same structures would if they were planned for the United States.

Wildlife is only one aspect of the conflicts that arise when observatories are built in remote locations. Some look upon observatories as scars on the landscape. Construction styles have slowly changed to accommodate such viewpoints. For example, the Mount Graham "domes" are actually below the tree line. They are boxlike enclosures, not visible from remote distances. There have been persistent complaints about the telescopes atop Mauna Kea in Hawaii, which stand out because of the absence of trees there. More often than not, however, local residents take pride in the observatories located in their communities.

The interaction between observatories and their environments is an old one. The telescopes on Mount Wilson, overlooking the Los Angeles basin, are still some of the finest in the world, but the growth of the local population has greatly reduced the effectiveness of observations from this location. In fact, many of the newest observatories sensitive to wavelengths across the electromagnetic spectrum are being built far from current human habitation and far from places that humans are ever likely to inhabit. The Atacama Large Millimeter Array, described in more detail in Chapter 2, will be located in an environment perfect for millimeter wave astronomy but dangerous to humans because of its very high elevation. The array will be constructed at an elevation of 5,000 m in Cerro Chajnantor, northern Chile. As more and more telescopes are built in remote locations and even launched into orbit, conflicts between newly built telescopes and local communities are likely to diminish.

Radio telescopes require a lot of physical space because of the large size of radio waves. The resolution of a telescope is proportional to the ratio of the observing wavelength to the diameter of the primary mirror or reflective surface. More specifically, the resolution of a telescope in arcseconds is (approximately)

$$\Theta = 206265 \lambda/D$$

where λ is the wavelength of the observations, and D is the diameter of the telescope, or the greatest distance between any two telescopes in an interferometer (see Chapter 2; this length is called a *baseline*). The factor in front simply converts the result from radians to arcseconds. For this reason, telescopes that detect radio waves must be proportionately larger than optical telescopes. Thus the world's great radio telescopes, such as the Very Large Array in New Mexico and the Arecibo radio telescope in Puerto Rico, require a great deal of space. In its largest configuration, the most widely separated telescopes of the VLA are approximately 35 km apart. The Arecibo "dish" fills an entire valley with a diameter of 1,000 m (Figure 3.2). While the fraction of the world's surface that is "marred" by these telescopes is quite small, local residents may or may not appreciate the impact on their environment.

Light Pollution

The presence of an observatory in a community often has the beneficial effect of raising local awareness of light pollution. Light pollution is defined as scattered or misdirected light produced by streetlights or other typical urban light sources. Photons that go up into the atmosphere either directly or as reflected light off of surfaces beneath them do nothing to increase safety but can wreak havoc on the ability to view the night sky (Figure 3.3). Recently, the topic has been in the news. Some communities, especially those close to "dark-sky" sites used by local amateur astronomers, even have restrictions written into the covenants of new subdivisions in which homeowners commit to the use of full-cutoff fixtures around their homes. Most of the problems of light pollution are due to ignorance, not malice, and can be solved simply by education.

The International Dark-Sky Association (IDA), based in Tucson, Arizona, maintains an extensive Web site on the problem of light pollution and the tangible ways that individuals and communities can reduce it, save energy, and preserve the natural resource of the night sky (http://www.darksky.org/ida/). This organization's actions have led to strict light pollution controls in and around Tucson, which have directly increased the usable lifetime of the observatories on the nearby desert mountaintops.

Less appreciated sources of light pollution are those that affect radio astronomers. Radio interference in the age of mobile telecommunications has become a serious problem for astronomical observation outside of the visible spectrum.

Figure 3.2. An aerial view of the 305-m-diameter Arecibo radio telescope in Puerto Rico. The observatory has a new visitor's center located in the lower part of the image; cars parked near the building give a sense of scale. Radio frequency receivers are located in the 900-ton platform suspended over the primary reflective surface. Arecibo Observatory is operated by the National Astronomy and Ionosphere Center (NAIC). Courtesy of the National Astronomy and Ionosphere Center.

THE COSTS OF ASTRONOMY

Despite the large amounts of money that some amateurs spend on their hobby, it costs almost nothing for most people who live under dark skies to go outside and enjoy the view. For the professional astronomer, however, costs can be quite significant. While the cost of astronomy is tiny in comparison, for example, to the U.S. military budget, the federal government does spend a significant amount of money on astronomy and astronomical research, and it is reasonable for citizens to wonder whether the investment is worthwhile to society. First, exactly how much is spent on astronomy?

The NASA budget for fiscal year (FY) 2001 was $14.3 billion, out of a total federal discretionary budget of just over $633 billion. Discretionary amounts do not include payments on the federal debt or mandatory entitlement expenditures such as Medicare, welfare, or social security. Only about 2.5 billion of NASA's total budget is spent

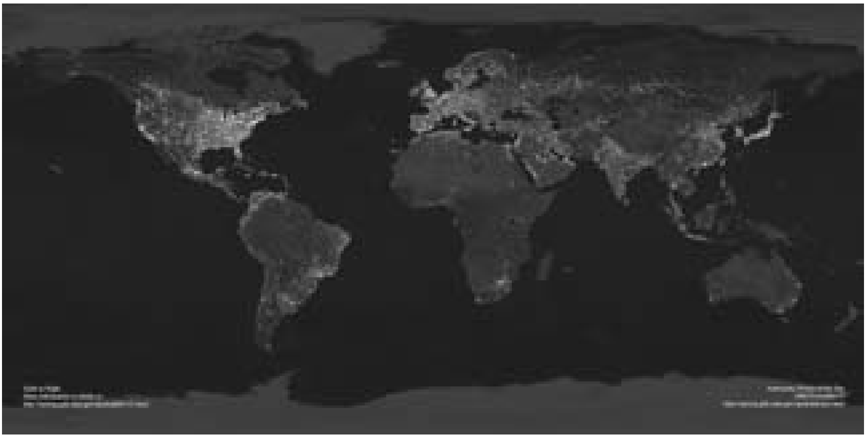

Figure 3.3. This view of the Earth from space is a composite of many hundreds of Defense Meteorological Satellites Program (DMSP) images. Note that "light pollution" traces the populated areas of the Earth's surface, with bright points of light marking the planet's great cities. This leaking light brightens the blackness of the night sky and makes the stars, planets, and the Milky Way less visible from much of the Earth's surface. Image by Craig Mayhew and Robert Simmon, NASA Goddard Space Flight Center (GSFC), based on DMSP data courtesy of Christopher Elvidge, National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center.

directly or indirectly on astronomy or space science research. The total NASA budget accounts for about 2.3 percent of the federal discretionary budget. A little over 2 percent may not sound like a large number, but it is interesting to note that the NASA budget is one of the larger outlays that the government makes. NASA's budget in FY 2000, $13.6 billion, was much larger than our international assistance program and comparable in size to the same year's outlays for the Department of Agriculture, $15.4 billion. However, while the federal discretionary budget is projected to grow through FY 2005, NASA funding is projected to grow more slowly and will thus represent a smaller share of the overall budget each year. What are the federal dollars spent on NASA supporting?

NASA's budget is typically divided into four major categories: Space Science, Earth Science, Space Transportation Technology, and Human Exploration and Development of Space (HEDS). In the proposed budget for FY 2001, HEDS is proposed to get the lion's share of the funding, or about $5.5 billion. These dollars support the continuing construction and staffing of the International Space Station (ISS) and the launch and maintenance of the space shuttle program. Space Science, or the support of basic research into the way the universe works (e.g., how stars form, how galaxies evolve), amounts to $2.4 billion.

The other major supporter of basic astronomy research is the National Science Foundation. The proposed level of support for FY 2001 was $4.6 billion. Of this, about half of the funds go to support facilities and efforts in education and training, and the other half goes to support basic research. So astronomy competes with all of the other sciences for the $2 billion or so dollars that go to support basic research from the NSF. The entire National Science Foundation was funded in FY 2000 at the level of $3.9 billion, and a small fraction of those dollars is spent on basic astronomy research. NSF has broadly defined directorates that distribute money to researchers. Within these directorates are divisions responsible for funding specific sciences. The Astronomy (AST) division is located within the Mathematics and Physical Sciences (MPS) Directorate. MPS gets the largest share of the NSF budget, but the total astronomy budget was only $123 million for FY 2000. The National Science Foundation, for example, is the source of funding for the Very Large Array, the world's premier radio interferometer, which celebrated 20 years of science in 2000.

In all, then, the federal government supports basic research in astronomy at the level of about $2.5 billion. For a comparison, the defense budget for FY 2000 was about $270 billion, so for every dollar that we spend on defense, we spend about a penny on astronomy. What impact does this spending have? Some of the most compelling science news from the past year has been discoveries made with federally funded telescopes or research. The Hubble Space Telescope (part of the NASA budget) continues to produce stunning astronomical discoveries and images. The VLA and the Very Long Baseline Array (both funded and administered as observatories under the National Science Foundation) have produced images and spectra of some of the most distant objects known. The Very Long Baseline Array in addition has provided data that challenges the distance scale in the universe as proposed by results from the Hubble Space Telescope.

The ongoing exploration of the solar system, funded by NASA, continues to amaze people the world over. Discoveries from the Galileo mission to Jupiter and its moons, the discovery of water on the moon as a result of the Lunar Prospector mission, the high-resolution imaging of the surface of Mars by Mars Global Surveyor—these are discoveries that are at the very edge of human capability. The discoveries made by these missions have a lasting effect on our collective psyche and continue the tradition of astronomers confronting society again and again with new knowledge and new perspectives on our place in the world. While there have been notable failures (see Chapter 1), NASA's new "Faster, Better, Cheaper" approach has produced some great successes. The idea recently has been to fund a larger number of less expensive missions, with the understanding that each mission might produce a smaller number of results. And the failure of a single mission, when so many are planned, would not have a catastrophic effect on the overall program.

Finally, we touch on the topic of the interaction between military technology and astronomy. From the beginning, technology that has been attractive to astronomers has also been attractive to military leaders. Telescopes that could see ships at great distances (as Galileo demonstrated to the political and military leaders of Venice in the first decade of the seventeenth century) were also able to produce magnified images of the surfaces of the moon and planets. Radar installations that can reflect radio waves off enemy aircraft can be modified to detect faint radio waves from space. And sensitive infrared detectors that can pinpoint the emission from young protostars can also be used to lock onto the emission from the exhaust of a military aircraft. Clearly, astronomers do not have the first go at these technologies as they come on line, but the same companies that build the nation's national defense infrastructure (e.g., Lockheed, Ball Aerospace) are also some of the primary bidders for large federally funded astronomical projects. These companies that have the greatest level of experience in building and launching military satellites surely enjoy a competitive advantage when building an orbiting telescope.

Perhaps one of the main beneficial social impacts of astronomy is to take technologies that may have been developed for other purposes and use them to discover more about our universe. So we return to where we began. The desire of rulers to predict the future through an accurate knowledge of planetary positions (astrology) and accurately to keep time for business and agriculture in ancient times apparently led to careful record keeping about the relative positions of objects in the skies and the origin of astronomy. The government's current desire to maintain a strong defense has in some cases made valuable new technology available to astronomers who are able to put the technology to alternative, more peaceful, and more significant uses.

Astronomers are often faced with the task of justifying what they do. If most people are asked what practical benefits society has gained from astronomy, they are likely to think of examples from the space program. Certainly, the computing- and technology-intensive requirements of the space program in the 1960s are related to the explosion in these areas during that decade and ever since. But most citizens would be hard-pressed to come up with practical benefits of basic astronomical research, explorations into how stars form, how galaxies evolve, or what is the source of intense sources of gamma ray emission called gamma ray bursters. Astronomers are increasingly aware of the need to clearly communicate their findings to the society that often pays the bill.

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Chapter Four

Documents and Sources

In this chapter, we present a number of original documents that expand on topics presented in other chapters of the book. These documents give a unique perspective on the rich variety of astronomical inquiry and its intersection with public policy concerns, federal budget issues, city planning, long-range space exploration, and basic human curiosity. These excerpts provide a relatively unfiltered look at astronomy at the beginning of the twenty-first century.

The introductory materials for each segment are the authors', as well as any bracketed material inserted in the original documents. The remainder of the materials in this chapter are public documents, available in their entirety in print form or via the Internet. They relate to public funding of astronomy, light pollution, the loss of NASA spacecraft, the search for extrasolar planetary systems, astrobiology, and the international effort to track near-Earth objects (NEOs).

PUBLIC FUNDING OF ASTRONOMY AND ASTROPHYSICS RESEARCH

The Committee on the Organization and Management of Research in Astronomy and Astrophysics (COMRAA) Report

During the budget process in the early part of 2001, the Bush administration suggested that the astronomical community (as represented by a blue ribbon panel of astronomers) consider the roles of the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA). The concern on the part of the administration was that NASA and the NSF avoid any duplication of effort in the investigations of the universe that they were supporting. The Committee submitted its report, a 68-page document, on September 5, 2001. The following are excerpts from the report. The complete report may be found at http://www.nas.edu/bpa/projects/brp/comraa-prepub_9-4-01.pdf.

If the interagency planning board that is proposed in this document is formed and empowered, it will have a large impact on the long-term planning and execution of astronomical research in the United States in coming decades.

EXECUTIVE SUMMARY

In its fiscal year 2002 budget summary document[1] the Bush administration expressed concern—based in part on the findings and conclusions of two National Research Council studies—about recent trends in the federal funding of astronomy and astrophysics research.[2] The President's budget blueprint suggested that now is the time to address these concerns and directed the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) to establish a blue ribbon panel to (1) assess the organizational effectiveness of the federal research enterprise in astronomy and astrophysics, (2) consider the pros and cons of transferring NSF's astronomy responsibilities to NASA, and (3) suggest alternative options for addressing issues in the management and organization of astronomical and astrophysical research. NASA and NSF asked the National Research Council to carry out the rapid assessment requested by the President. This report, focusing on the roles of NSF and NASA, provides the results of that assessment.

Overall, the federal organizations that support work in astronomy and astrophysics manage their programs effectively. These programs have enabled dramatic scientific progress, and they show excellent promise of continuing to do so. Nonetheless, the existing management structure for the U.S. astronomy and astrophysics research enterprise is not optimally positioned to address the concerns posed by the mounting changes and trends that will affect the future health of the field.

The existing management structure for astronomy and astrophysics research separates the ground- and space-based astronomy programs. NSF has responsibility for the former and NASA has responsibility for the latter. The ground-based optical/infrared observatories funded by private and state resources constitute an important third component of the system. In astronomical and astrophysical research, NASA's strength has been the support of work related to major space missions. NSF's strength in astronomy and astrophysics has been the support of a broad spectrum of basic research motivated by the initiative of individuals and small groups in the scientific community and by its role in assuring the continued availability of broadly educated scientists. The NSF also funds research in related fields such as physics, geophysics, computation, chemistry, and mathematics, providing a broad multidisciplinary context for astronomy and astrophysics research that can promote productive connections among these fields.

Three important changes have occurred in the field over the last two decades. First, ground- and space-based research activities have become increasingly interdependent as well as increasingly reliant on large facilities, major missions, and international collaborations. Second, NASA's relative role in astronomy and astrophysics research has grown markedly. (In 1980, most of the research grants in the fields of astronomy and astrophysics were provided by NSF. Today, most of the grants are provided by NASA.)[3] And third, large state-of-the-art optical/infrared telescopes built with non-federal funds now dominate this component of ground-based astronomy.

These changes necessitate systematic, comprehensive, and coordinated planning in order to sustain and maximize the flow of scientific benefits from the federal, state, and private investments that are being made in astronomy and astrophysics facilities and missions. The increasing financial and intellectual demands to be met by more than one nation in supporting large projects, particularly on the ground, require that the United States develop a unified planning and execution structure to effectively participate in such international ventures. To develop the needed integrated and comprehensive strategy for the field, the committee recommends the formation of an interagency planning board for astronomy and astrophysics.

[Here the committee addresses one of its major charges, to determine whether NASA should take on the funding responsibilities that had been under the NSF.]

The Committee on the Organization and Management of Research in Astronomy and Astrophysics was charged to consider, among other options, moving NSF's astronomy responsibilities to NASA.[4] Such a move would consolidate the bulk of the federal programs[5] in a single agency and, to some degree, integrate space- and ground-based astronomy. The committee concluded, however, that moving NSF's astronomy and astrophysics activities to NASA would have a net disruptive effect on scientific work. Because of its combined commitment to investigator-initiated research, interdisciplinary research, and educating the scientists of the future, NSF is the right institution to sponsor ground-based astronomy and astrophysics. And further, such a move would not necessarily address integration of the third component of the system (i.e., the ground-based optical/infrared private and state observatories). NSF's close working relationship with the college and university community makes it the natural focus for integration of this third component. The committee's recommendations address improving the present overall management structure, as well as strengthening NSF's ability to support ground-based astronomy and astrophysics and to work effectively in conjunction with the other two primary components of the system.

The committee's detailed recommendations are contained [below].

RECOMMENDATIONS OF THE COMMITTEE

1. The National Science Foundation's astronomy and astrophysics responsibilities should not be transferred to NASA.
2. In order to maximize the scientific returns, the federal government should develop a single integrated strategy for astronomy and astrophysics research that includes supporting facilities and missions on the ground and in space.
3. To help bring about an integration of ground- and space-based astronomy and astrophysics, the Office of Science and Technology Policy and the Office of Management and Budget should take the initiative to establish an interagency planning board for astronomy and astrophysics. Input to the planning board from the scientific and engineering community should be provided by a joint advisory committee of outside experts that is well connected to the advisory structures within each agency.

   —The recommended interagency Astronomy and Astrophysics Planning Board, with a neutral and independent chair to be designated by the Office of Management and Budget in conjunction with the Office of Science and Technology Policy, should consist of representatives of NASA, NSF, the Department of Energy, and other appropriate federal agencies such as the Smithsonian Institution and the Department of Defense. The Planning Board should coordinate the relevant research activities of the member agencies and should prepare and annually update an integrated strategic plan for research in astronomy and astrophysics, addressing the priorities of the most current National Research Council decadal survey of the field in the context of tight discretionary budgets.

      —The membership of the Planning Board's advisory committee should be drawn in part from the external advisory panels of the Planning Board's member agencies. The advisory committee should be chaired by an individual who is neither a member of the agency advisory panels nor an agency employee. The committee should participate in the development of the integrated strategic plan and in the periodic review of its implementation.

4. NASA and NSF should each put in place formal mechanisms for implementing recommendations of the interagency Astronomy and Astrophysics Planning Board and integrating those recommendations into their respective strategic plans for astronomy and astrophysics. Both agencies should make changes, as outlined below, in order to pursue effective roles in formulating and executing an integrated federal program for astronomy and astrophysics. These changes should be coordinated through the interagency Planning Board to clarify the responsibilities and strategies of the individual member agencies.
5. The NSF, with the active participation of the National Science Board, should:
    a. Develop and implement its own strategic plan, taking into account the recommendations of the interagency Planning Board. Its strategic plan should be formulated in an open and transparent fashion and should have concrete objectives and time lines. NSF should manage its program in astronomy and astrophysics to that plan, ensuring the participation of scientifically relevant divisions and offices within NSF. To help generate this plan, NSF should reestablish a federally chartered advisory committee for its Astronomical Sciences Division to ensure parity with the NASA advisory structure. The chair of this Astronomical Sciences Division advisory committee should be a member of the Mathematical and Physical Sciences Directorate advisory committee. Furthermore, the Mathematical and Physical Sciences Directorate advisory committee should make regular written and oral reports of its key findings and recommendations to the National Science Board.
    b. Address the outstanding issues that are affecting ground-based astronomy at present.

        —Lead the development of an integrated strategy for assembling the resources needed to build and operate the challenging suite of ground-based initiatives recommended by the most current decadal survey.

        —Work to create an integrated system for ground-based optical/infrared astronomy and astrophysics encompassing private, state, and federally funded observatories, as advocated by the decadal survey.

        —Improve and systematize the process for initiating, constructing, managing, and using ground-based facilities, so that it includes:

—clear lines of authority for negotiations, particularly those involving international partners,

—an open bidding process for contracts,

—comprehensive budgeting that provides for all aspects and phases of projects, and

—provision of the resources required to exploit the scientific potential of the facilities, including associated instrumentation, theoretical work, data analysis, and travel.

[The following recommendation if implemented could significantly raise the public awareness of research being done by many non-NASA facilities. The skill and funding of NASA public relations often means that NASA-funded results are far better publicized than those from non-NASA facilities.]

c. Undertake a more concerted and well-funded effort to inform the press and the general public of scientific discoveries, and cooperate with NASA in developing a coordinated public information program for astronomy and astrophysics.

6. In parallel, NASA should:.
   a. Implement operational plans to provide continuity of support for the talent base in astronomy and astrophysics should critical space missions suffer failure or be terminated.
   b. Continue and enlarge its program of research support for proposals from individual principal investigators that are not necessarily tied to the goals of specific missions.
   c. Support critical ground-based facilities and scientifically enabling precursor and follow-up observations that are essential to the success of space missions. Decisions on such support should be considered in the context of the scientific goals articulated in the integrated research plan for astronomy and astrophysics.
   d. Cooperate with NSF in developing a coordinated public information program for astronomy and astrophysics.

NOTES

1. Executive Office of the President, *A Blueprint for New Beginnings: A Responsible Budget for America's Priorities*, U.S. Government Printing Office, Washington, D.C., 2001.

2. This trend was noted in *Federal Funding of Astronomical Research.*

3. The two National Research Council reports are *Federal Funding of Astronomical Research* (2000) and *Astronomy and Astrophysics in the New Millennium* (2001), National Academy Press. Washington, D.C.

4. It would be unreasonable to consolidate under NSF, i.e., to place space missions, under NSF, since NSF has no space experience, does not operate its own facilities, and does not have a large enough budget to carry out space missions.

5. Additional important federal components include the Department of Energy, which conducts research in particle, high-energy, nuclear, and plasma physics and in computational science related to astronomy and astrophysics; the Smithsonian Institution, which plays a significant role in astronomy and astrophysics research through the Smithsonian Astrophysical Observatory; and the Department of Defense, which supports research in areas such as solar physics, astrometric astronomy, and observing technology that is carried out primarily through multiple programs in the Navy and Air Force research offices.

PLANNING FOR FUTURE PROGRESS

The astronomy and astrophysics community has a unique 50-year tradition of surveying the status of the field at 10-year intervals and setting consensus priorities for the recommended scientific and programmatic directions of the field for the next decade. The preparation of these surveys involves a significant fraction of the astronomy and astrophysics community. Each of the surveys has set ambitious targets for both the community and their federal sponsors, and these survey reports have been remarkably successful in providing blueprints for use by decision makers in the executive branch and Congress. Scientists and scientific organizations around the world also use the survey reports as benchmarks for future trends in the field.

The conclusions and recommendations of the most recent survey report (*Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001), together with a companion National Research Council (NRC) report that examined recent trends in the funding and demographics for astronomical and astrophysical research (*Federal Funding of Astronomical Research*, National Academy Press, Washington, D.C., 2000), have important implications in the context of this study. These two reports raised concerns that in spite of the vigorous pace of scientific developments in contemporary astronomy and astrophysics, there are warning signals and trends that require attention if the field is to continue on this productive path well into the future. These trends were, to a large degree, what prompted the call for potential reform in the Bush administration budget blueprint. It is these issues that the current study attempts to address.

Issues Discussed in Recent National Research Council Assessments of the Discipline

[Some of the details of this report are summarized in Chapter 8.]

FEDERAL FUNDING STUDY

The National Research Council report *Federal Funding of Astronomical Research* (National Academy Press, Washington, D.C., 2000) found that over the last two decades, the balance of research grant support has shifted away from NSF and toward NASA. The report attributed most of this trend to a significant increase in research grants connected to astronomy and astrophysics missions launched by NASA during a time when growth in funding for NSF astronomy research grants was barely keeping pace with inflation. (This increase in astronomy and astrophysics research grants at NASA was due largely to the integrated research programs of the flagship missions, or so-called "Great Observatories"—the Hubble Space Telescope, Compton Gamma-Ray Observatory, Chandra X-ray Observatory, and Space Infrared Telescope Facility.) In particular, NSF's share of federal support for grants to researchers in the discipline fell from 60 percent at the beginning of the 1980s to 30 percent at the end of the 1990s.

The report found that this shift had produced imbalances—for example, funding for broad-based astrophysical theory has not kept pace with the research funding for the field as a whole. And it found that the number, size, and capability of ground-based observing facilities have increased considerably without a commensurate increase in NSF funds for utilizing the facilities. The report suggested including in the plan for each new initiative a strategy for accomplishing its scientific mission. It identified a number of elements that should be included in the strategy, among them funds for enabling instrumentation, for observations and analysis, and for theoretical studies. Finally, the report observed that much of the support of astronomy and astrophysics is now tied to a few flagship NASA missions, making the dependent research community vulnerable to a catastrophic failure of one of these large missions.

[The Decadal Survey Reports are the result of input from across the astronomical community. One needs only to look back at past decadal reports to see the origin of such missions as the Very Large Array, the Hubble Space Telescope, and other now-familiar missions.]

DECADAL SURVEY REPORT

The most recent decadal survey prepared under the auspices of the National Research Council is *Astronomy and Astrophysics in the New Millennium* (National Academy Press, Washington, D.C., 2001). The report begins with a proposed scientific program for the next decade, describes the ground- and space-based facilities necessary to achieve that program, and then discusses policy recommendations relevant to the current and future health of the field.

The ambitious overarching scientific goal for the field as stated in the decadal survey report is "to develop a comprehensive understanding of the formation, evolution, and destiny of the universe and its constituent galaxies, stars, and planets—including the Milky Way, the Sun, and Earth" (p. 3). The report then proposed five areas that are ripe for significant progress in the next decade. With those major scientific goals as a foundation, the report recommended a set of prioritized initiatives for the next decade. The new recommended initiatives have two important aspects. First, they are extremely challenging. Second, space- and ground-based astronomy and astrophysics each have critical roles, with high-priority projects in both arenas in roughly equal numbers. For example, the science goal of determining the large-scale properties of the universe is addressed by a combination of the Next Generation Space Telescope (NGST; a successor to the Hubble Space Telescope), the Giant Segmented Mirror Telescope (GSMT; a major advance in ground-based telescopes), and the Large-Aperture Synoptic Survey Telescope (LSST; a ground-based survey telescope). All three future facilities are needed to address this science goal because NGST will image the most distant objects in the visible universe, GSMT will characterize the physical properties of these objects, and LSST will study the nature of the dark matter and dark energy that pervade the universe. NASA plays the crucial role in realizing NGST at a federal cost of nearly $1 billion. As conceived, GSMT and LSST would represent the most ambitious efforts ever undertaken in the NSF astronomy program, with a combined federal cost of more than $500 million out of total project costs of nearly $1 billion. NGST is already an international effort, and the two ground-based projects will almost certainly be multinational projects with significant contributions from the private sector.

[There is a pervasive note of caution in these reports against putting all the eggs in one basket, or at least in a small number of baskets.]

The policy section of the decadal survey report concluded, in addressing organization and management issues raised by the Congress, that the astronomy and astrophysics research enterprise is currently robust and generally healthy. But the report goes on to express concerns similar to those found in *Federal Funding of Astronomical Research*, namely, that the balance among various components of the program (especially between the NSF and NASA grants programs) remains a concern, and that a large portion of the total support for astronomy is now tied to a few NASA flagship missions.

To address the question of balance, the decadal survey report recommended several steps to strengthen the ground-based program, including the following:

- National and independent observatories should be viewed as integrated systems of capabilities for the United States as a whole.

- Funds for grants for data analysis and the development of associated theory should be included in the budgets of major new ground-based facilities for their first 5 years of operation.
- The NSF should take more initiative in sharing with the general public the results of the scientific investigations NSF supports.

The decadal survey report further encouraged cooperation among NASA, NSF, and, for some projects, DOE [Department of Energy]. It recommended that these agencies work together with the research community to build new interagency programs and observed that the Office of Science and Technology Policy is the traditional broker for such cooperation.

[The following recommendation addresses a major concern for observers who utilize facilities like the Very Large Array. Astronomers must apply for observing time and separately apply to funding agencies (like the NSF) for the funds to support the reduction and publication of the results. The recommendation is that the NSF act more like NASA, including funds for support that are granted along with observing time.]

The survey report also pointed out that at NSF provision of funds for research and analysis to capitalize on the observations made possible by new facilities is often neglected. Moreover, the NSF astronomy grants program is under heavy pressure to fund the analysis of the data obtained at these national ground-based facilities and the private/state observatories. This disconnect between facilities and the funds necessary to operate them differs from the results of NASA's policy of explicitly tying research funding to the successful peer-reviewed proposals for observations from a space mission. The report recommended that NSF include funding for operations, new instrumentation, and data analysis and theory grants for the first 5 years of operation when budgeting for each new large ground-based facility.

LIGHT POLLUTION

Light pollution has been in the news in recent years as the result of a couple of well-publicized pictures of the Earth as seen from space. These pictures show the large amount of light (and energy) that is wasted by our conventional lighting. The following document is excerpted from groups that support the use of "smart lighting" that can ensure safety as well as the beauty of dark skies at night. While this presentation may seem one-sided, there is really no group that supports light pollution. Generally, companies are happy to achieve both the good public image and the energy savings that come along with careful planning of outdoor lighting. The difficulty comes more with the expense and effort required to replace outdated lighting fixtures with new ones, even though the old fixtures might still be in working condition. The excerpt is from a document produced by the International Dark-Sky Association (IDA).

We All Win by Correcting the Problems of Inefficient Outdoor Lighting at Night

- Many types of outdoor lighting designed for advertising, security and visibility are actually wasteful, invasive and a source of disabling glare.
- "Light trespass," the poor control of outdoor lighting which crosses property lines, detracts from our quality of life, and confuses the instinctive daily and seasonal cycles of animals and plants.
- Although perceived as a deterrent to crime, studies by the US Department of Justice and the National Institute of Justice show no conclusive evidence that lighting actually prevents crime.
- Public hazards have been created by the use of glaring, high-wattage floodlighting along roadways and business parking lots, shining directly in the driver's line of sight.
- Public safety is also being compromised by businesses competing with light levels to attract business. The eye's inability to adjust quickly to drastic changes from light to dark leaves a driver temporarily blind when exiting an overlit business area at night. It is not uncommon to see businesses using 3 to 6 times the recognized, lighting industry recommendations for site lighting (IESNA [Illuminating Engineering Society of North America]).
- The recent awareness of global warming concerns, due in a large part to power plant emissions, now demands an effort to reduce our consumption of electricity.
- Because of this unnecessary condition, many of our children today have already lost much of the starry night sky behind the glow of wasted light, limiting their imaginations to the man-made boundaries around them.
- By correcting these outdoor lighting problems for the future we can save money and electricity, improve public safety and increase visibility, while reducing air pollution and greenhouse gas emissions.

For more information, contact: The International Dark-Sky Association, 3225 N. First Ave., Tucson AZ 85719—520-293-3198—website: http://www.darksky.org.

WOMEN IN ASTRONOMY

In 1992, Meg Urry and other astronomers organized a conference titled "Women in Astronomy." The conference discussions eventually led to the publication of a document called *The Baltimore Charter for Women in Astronomy*. The document proposes that women have long been contributors to the discipline and that efforts should be made to ensure that women will be allowed to contribute equally in the future. The charter is presented in its entirety below.

The Baltimore Charter for Women in Astronomy

PREAMBLE

We hold as fundamental that:

Women and men are equally capable of doing excellent science.

Diversity contributes to, rather than conflicts with, excellence in science.

Current recruitment, training, evaluation and award systems often prevent the equal participation of women.

Formal and informal mechanisms that are effectively discriminatory are unlikely to change by themselves. Both thought and action are necessary to ensure equal participation for all.

Increasing the number of women in astronomy will improve the professional environment and improving the environment will increase the number of women.

This Charter addresses the need to develop a scientific culture within which both women and men can work effectively and within which all can have satisfying and rewarding careers. Our focus is on women, but actions taken to improve the situation of women in astronomy should be applied aggressively to those minorities even more disenfranchised.

RATIONALE

Astronomy has a long and honorable tradition of participation by women, who have made many significant and highly creative contributions to the field. Approximately 15% of astronomers worldwide are women, but there is wide geographical diversity, with some countries having none and others having more than 50%. This shows that scientific careers are strongly affected by social and cultural factors, and are not determined solely by ability. The search for excellence which unites all scientists can be maintained and enhanced by increasing the diversity of its practitioners. Great discoveries have always occurred in times of cross-cultural enrichment: along trade routes, in periods of geographical exploration, among immigrants and multinationals. The introduction of new approaches frequently results in new breakthroughs. Achieving such diversity requires revised, not lesser, criteria for judging excellence, free of culturally-based perceptions of talent and promise.

A review of available information on the relative numbers and career histories of women and men in science reveals extensive discrimination. Access to the profession—graduate education, hiring, promotion, funding—is not always independent of gender. Unequal treatment of women in the laboratory, the lecture hall and the observatory, more subtle but at least as important as overt discrimination, creates a chilly climate which discourages and distresses women, alienates them from the field, and ultimately damages the profession.

Existing inequities can be eliminated only partially by legal stricture or they would not continue today. Improving the situation requires awareness of the very real barriers women currently face, including sexual stereotyping, opportunity and pay differentials, inappropriate time limits on advancement, overcritical scrutiny and sexual harassment. Sexual harassment, ranging from an uncomfortable work environment to unwanted sexual attention to overt extortion of sexual favors, can force confrontation between junior astronomers and older, better established colleagues who can strongly influence career advancement; it diverts attention from science to sex, places an undue burden on the harassed, and damages their self-esteem.

The entire profession must assume the immediate and ongoing responsibility for implementing strategies that will enable women to succeed within the existing structures of astronomy and allow the desired acceptance of diversity to develop fully.

RECOMMENDATIONS

Significant advances for women have been made possible by affirmative action. Affirmative action involves the establishment of serious goals, not rigid quotas, for achieving diversity in all aspects of the profession, including hiring, invited talks, committees, and awards.

(a) Standards for candidates should be established and publicized in advance. Criteria that are culturally based or otherwise extraneous to performance or the pursuit of scientific excellence should not be applied.

(b) Women should participate in the selection process. If insufficient numbers of women are available at particular institutions, outside scientists can be invited to assist. Men must share fully the responsibility for implementing affirmative action, as they hold the majority of leadership positions.

(c) The selection of women should reflect on average their numbers in the appropriate pool of candidates and normally at least one woman should be on the short list for any position, paid or honorific. When women are underrepresented in the pool, their numbers should be increased by active and energetic recruitment.

(d) Demographic information for each astronomical organization should be widely publicized. If the goals for affirmative action are not achieved, the reasons must be determined.

The criteria used in hiring, assignment, promotion and awards should be broadened in recognition of different pacing of careers, care of older and younger family members, and demands of dual-career households. Provision for day care facilities, family leave, time off and re-entry will instantly improve women's access to an astronomical career and is of equal benefit to men.

Strong action must be taken to end sexual harassment. Education and awareness programs are standard in U.S. government and industry and should be adopted by the astronomical community. Each institution should appoint one or more women to receive complaints about sexual harassment and to participate in the formal review process. Action against those who perpetrate sexual harassment should be swift and substantial.

Gender-neutral language and illustrations are important in the formation of expectations, both by those in power and those seeking entrance to the profession. Documents and discussions should be sensitive to bias that favors any one gender, race, sexual orientation, life style, or work style. Those who represent astronomy to the public should be particularly aware of the power of language and images which, intentionally or unintentionally, reflect on astronomy as a profession.

Physical safety is of concern to all astronomers and of particular significance to women, who often feel more vulnerable when working alone on campus or in observatories. This issue must be addressed by those in a position to affect security, making it possible for everyone to work at any hour, in any place, as necessary.

CALL TO ACTION

Improving the situation of women in astronomy will benefit, and is the responsibility of, astronomers at all levels. Department heads, observatory directors, policy committee chairs, and funding agency officials have a particular responsibility to facilitate the full participation of women: to nurture new talent, to ensure the effectiveness of teaching, and to examine and correct patterns of inequity. The profession should be responsible for regular review and assessment of the status of women in astronomy, in pursuit of equality and fairness for all.

A rational and collegial environment which allows full expression of intellectual style is necessary for achieving excellence in scientific research. Women should not have to be clones of male astronomers in order to participate in the mainstream of astronomical research. Women want and deserve the same opportunity as their male colleagues to achieve excellence in astronomy.

THE LOSS OF NASA SPACECRAFT

As has been discussed in other chapters of this book, several spacecraft were lost while en route to Mars in the late 1990s. While some losses must be expected in any venture as large as the exploration of the solar system, the studies that were carried out in the aftermath of the Mars Climate Orbiter loss were particularly embarrassing for the contractors involved. The following is an excerpt from the report of the Mishap Investigation Board (MIB).

Mishap Investigation Board (MIB) Report

EXECUTIVE SUMMARY

This Phase I report addresses paragraph 4.A. of the letter establishing the Mars Climate Orbiter (MCO) Mishap Investigation Board (MIB) (Appendix). Specifically, paragraph 4.A. of the letter requests that the MIB focus on any aspects of the MCO mishap which must be addressed in order to contribute to the Mars Polar Lander's safe landing on Mars. The Mars Polar Lander (MPL) entry-descent-landing sequence is scheduled for December 3, 1999.

[It should be noted here that the Mars Polar Lander mission was also lost, though for apparently a different reason. Ground control tracked the MPL mission until entry into the Martian atmosphere and never established communication after that time.]

This report provides a top-level description of the MCO and MPL projects (section 1), it defines the MCO mishap (section 2) and the method of investigation (section 3) and then provides the Board's determination of the MCO mishap root cause (section 4), the MCO contributing causes (section 5) and MCO observations (section 6). Based on the MCO root cause, contributing causes and observations, the Board has formulated a series of recommendations to improve the MPL operations. These are included in the respective sections. Also, as a result of the Board's review of the MPL, specific observations and associated recommendations pertaining to MPL are described in section 7. The plan for the Phase II report is described in section 8. The Phase II report will focus on the processes used by the MCO mission, develop lessons learned, and make recommendations for future missions.

The MCO Mission objective was to orbit Mars as the first interplanetary weather satellite and provide a communications relay for the MPL which is due to reach Mars in December 1999. The MCO was launched on December 11, 1998, and was lost sometime following the spacecraft's entry into Mars occultation during the Mars Orbit Insertion (MOI) maneuver. The spacecraft's carrier signal was last seen at approximately 09:04:52 UTC [Coordinated Universal Time] on Thursday, September 23, 1999.

[Here the report gives the "root cause" for the failure. The failure was caused by a rather pedestrian mistake in the conversion of units that would have been a disappointment to any introductory physics professor.]

The MCO MIB has determined that the root cause for the loss of the MCO spacecraft was the failure to use metric units in the coding of a ground software file, "Small Forces," used in trajectory models. Specifically, thruster performance data in English units instead of metric units was used in the software application code titled SM FORCES (small forces). A file called Angular Momentum Desaturation (AMD) contained the output data from the SM FORCES software. The data in the AMD file was required to be in metric units per existing software interface documentation, and the trajectory modelers assumed the data was provided in metric units per the requirements.

During the 9-month journey from Earth to Mars, propulsion maneuvers were periodically performed to remove angular momentum buildup in the on-board reaction wheels (flywheels). These Angular Momentum Desaturation (AMD) events occurred 10–14 times more often than was expected by the operations navigation team. This was because the MCO solar array was asymmetrical relative to the spacecraft body as compared to Mars Global Surveyor (MGS) which had symmetrical solar arrays. This asymmetric effect significantly increased the Sun-induced (solar pressure–induced) momentum buildup on the spacecraft. The increased AMD events coupled with the fact that the angular momentum (impulse) data was in English, rather than metric, units, resulted in small errors being introduced in the trajectory estimate over the course of the 9-month journey. At the time of Mars insertion, the spacecraft trajectory was approximately 170 kilometers lower than planned. As a result, MCO either was destroyed in the atmosphere or re-entered heliocentric space after leaving Mars' atmosphere.

[This accident highlights how dependent astronomers and space scientists are on the computer models that determine where a spacecraft is at a given point in time. The models put the spacecraft as on the correct trajectory to enter the atmosphere. But that was not where the spacecraft was.]

The Board recognizes that mistakes occur on spacecraft projects. However, sufficient processes are usually in place on projects to catch these mistakes before they become critical to mission success. Unfortunately for MCO, the root cause was not caught by the processes in-place in the MCO project.

A summary of the findings, contributing causes and MPL recommendations are listed below. These are described in more detail in the body of this report along with the MCO and MPL observations and recommendations.

Root Cause: Failure to use metric units in the coding of a ground software file, “Small Forces,” used in trajectory models

Contributing Causes:

1. Undetected mismodeling of spacecraft velocity changes
2. Navigation Team unfamiliar with spacecraft
3. Trajectory correction maneuver number 5 not performed
4. System engineering process did not adequately address transition from development to operations
5. Inadequate communications between project elements
6. Inadequate operations Navigation Team staffing
7. Inadequate training
8. Verification and validation process did not adequately address ground software

MPL Recommendations:

- Verify the consistent use of units throughout the MPL spacecraft design and operations
- Conduct software audit for specification compliance on all data transferred between JPL and Lockheed Martin Astronautics
- Verify Small Forces models used for MPL
- Compare prime MPL navigation projections with projections by alternate navigation methods
- Train Navigation Team in spacecraft design and operations
- Prepare for possibility of executing trajectory correction maneuver number 5
- Establish MPL systems organization to concentrate on trajectory correction maneuver number 5 and entry, descent and landing operations
- Take steps to improve communications

- Augment Operations Team staff with experienced people to support entry, descent and landing
- Train entire MPL Team and encourage use of Incident, Surprise, Anomaly process
- Develop and execute systems verification matrix for all requirements
- Conduct independent reviews on all mission critical events
- Construct a fault tree analysis for remainder of MPL mission
- Assign overall Mission Manager
- Perform thermal analysis of thrusters feedline heaters and consider use of pre-conditioning pulses
- Reexamine propulsion subsystem operations during entry, descent, and landing

FUTURE MISSIONS: THE SEARCH FOR OTHER WORLDS

On a brighter note, many missions for the human exploration of the solar system, the galaxy, and the universe are planned for the coming decades. One of the most exciting ventures (as described in Chapter 1) is the search for planets orbiting other stars. As has been described in detail, astronomers have detected evidence for gas giants (Jupiter-sized planets) orbiting other stars, but there is a natural desire to look for systems that seem familiar, where small terrestrial planets also orbit. The following excerpt is from a planning document for the Terrestrial Planet Finder (TPF) mission. The passage from the executive summary gives an overview of the goals of the mission. The document highlights the interdependence of TPF with other missions and also emphasizes the importance of long-term planning in astronomy. Design contracts for TPF were awarded in early 2000.

Excerpt from Planning Document for Terrestrial Planet Finder (TPF) Mission

EXECUTIVE SUMMARY

Science Goals

The Terrestrial Planet Finder (TPF) will revolutionize humanity's understanding of the origin and evolution of planetary systems. TPF will allow us to identify habitable planets like our own Earth around the nearest stars and to assess how common they might be. By combining the sensitivity of space-borne telescopes with the high spatial resolution of an interferometer, TPF will study planets beyond our own solar system in a variety of ways: from their formation and evolution in the disks of newly forming stars to the properties of planets orbiting the nearest stars; from their numbers, sizes, locations, and diversity to their suitability as abodes for life. Using the technique of interferometric nulling, TPF will be able to reduce the glare of parent stars by a factor of more than one hundred thousand to reveal planetary systems as far away as 15 parsec (pc), or nearly 50 light years. The characterization of the size, temperature, and orbital parameters of entire planetary families, including bodies as small as the Earth in regions where liquid water might be expected to be stable, i.e. the "habitable zones," will reveal the diversity of planetary systems in our galactic neighborhood.

TPF will also use spectroscopy to measure the relative proportions of gases like carbon dioxide, water, ozone, and methane in the atmospheres of detected planets, to assess whether they might support life. The measurement requirements for TPF have been developed and will continue to be refined through detailed discussions with atmospheric chemists and biologists, including scientists participating in NASA's newly formed Astrobiology Institute.

TPF will advance our understanding of how planets and their parent stars form. The 250 year old nebular hypothesis of Kant and Laplace holds that planets originate in a flattened disk of material resulting from the collapse of a rotating cloud of gas and dust. While this theory has been strengthened by observations of protostellar disks that span tens to hundreds of astronomical units (AU) across, the recent discoveries of extrasolar planets with diverse orbital properties suggest that planetary systems are dynamic and that planets may migrate from the sites of their birth. As yet, we know almost nothing about the inner regions of protostellar disks where planet formation and migration is thought to occur. By studying the emission from dust, ices of water and carbon dioxide, and gases such as carbon monoxide and molecular hydrogen, TPF will provide essential information on the mass and temperature distribution across the protoplanetary cradle. This in turn will yield important clues on physical processes that determine how and where rocky and gaseous planets form. In the nearest star formation regions, TPF will resolve disk structures on the scale of a few tenths of an AU to investigate in detail how gaseous and rocky planets form out of disk material. The comparison of planetary systems around stars with different masses and ages will provide additional clues to the frequency with which habitable planets occur, allowing an estimate of the frequency of Earth-like planets through the cosmos as a whole.

Finally, TPF can investigate many other astrophysical sources where observations of milli-arcsecond structures are critical to understanding the essential physical processes. Combining the sensitivity of the Next Generation

Space Telescope (NGST) with mini-arcsecond imaging, TPF will be able to study such diverse topics as the winds from dying stars that enrich the interstellar medium with heavy elements or the nature of ultra-luminous objects at high redshift that may harbor black holes, enormous bursts of star formation, or other exotic phenomena.

Illustrative Mission Concept

This report reaffirms the conclusions of an earlier study (Exploration of Neighboring Planetary Systems (ExNPS) Report 1996) that an infrared interferometer represents the best approach to the challenge of detection and spectroscopic characterization of planets around nearby stars. . . . The primary goal of planet detection and characterization will utilize core wavelengths of 7 to 20 um and baselines of 75 to 200 m. . . . The present TPF observatory concept . . . can address whether a planet harbors primitive life in just two weeks of observation, roughly the time expended on the deep fields observed with the Hubble Space Telescope.

TPF's properties can be enhanced relative to what is necessary for planet detection with only small changes to the facility. For example, broader wavelength and baseline coverage will enable high dynamic range imaging of complex astrophysical sources with the milli-arcsecond resolution previously available only with very-long-baseline radio interferometry. Spectral resolution of a few hundred will isolate the emission of key gases such as molecular hydrogen and carbon monoxide. Still higher spectral resolution, approaching 100,000, is an instrumental option for selected spectral lines that would allow TPF to probe the dynamics of protostellar disks.

The present concept assumes four 3.5 m diameter telescopes, each on its own spacecraft, and a central spacecraft that houses the beam combining apparatus and astronomical instrumentation. TPF will orbit in an Earth-trailing, Space Infrared Telescope Facility (SIRTF)-like, orbit or at the Earth-Sun L2 point. Earlier designs, as described in the ExNPS report to NASA and the Darwin proposal to the European Space Agency (ESA), used 1–2 m telescopes on a connected truss operating in the low-background environment at 5 AU. The present concept leads to a robust systems-engineering and mission-design approach to TPF's challenges as well as enabling a broader range of scientific investigations. Other configurations involving four to six smaller telescopes, possibly 2–3 m segments identical to those developed by the Next Generation Space Telescope, are under active study by NASA and by ESA.

In the first year of its five-year mission, TPF will build on the astrometric results of the Space Interferometry Mission (SIM) to examine 150 solitary stars within 15 pc, to characterize planets discovered by SIM, as well as to extend the SIM census of planets to include planets as small as the Earth. Combined SIM and TPF data will allow a very detailed physical characterization of planets ranging in mass from Jupiter to a few times the Earth's mass. In subsequent years, TPF will carry out a program of spectroscopic follow-up of the most promising targets to search for habitable or inhabited planets, as well as in mapping a broad range of astrophysical targets.

[The following passage highlights the way in which missions are often built with technologies being "proven" in successive missions. Much of the technology necessary for the success of the TPF mission will be tested on missions that precede it, missions like the Next Generation Space Telescope (NGST) and SIM.]

Technology

While TPF presents many challenges, the key technologies are being addressed by a variety of NASA programs in preparation for the launch of TPF at the end of the next decade. At the beginning of TPF's development phase around 2006, the missions listed below will have demonstrated almost all of the key technologies needed for TPF. A few TPF-specific technologies will have to be developed in a carefully planned technology program.

- NGST will fly a cooled, 8 m light-weight mirror with cryogenic actuators and precision wavelength control. Smaller mirrors utilizing the same technology will be used by TPF.
- Ground-based interferometers such as the Keck Interferometer, the Large Binocular Telescope, and European Southern Observatories (ESO) Very Large Telescope Interferometer (VLTI) will develop hardware techniques, software packages, and a community that is ready to use TPF.
- The Space Interferometry Mission (SIM) will be a fully functional spaceborne interferometer that will demonstrate all aspects of interferometry including starlight nulling. SIM will demonstrate the pathlength control needed for TPF.
- The Space Technology Three mission (formerly known as Deep Space Three, or DS3) will demonstrate precision formation flight and nanometer pathlength control over a 1 km separation.
- Laboratory investigations have already begun to address the demanding requirements for deep interferometric nulling. Nulls as deep as one part in 25,000 have already been achieved in the laboratory.

Community Involvement

There will be numerous opportunities for involvement in TPF by the astronomical community through normal peer-reviewed channels, including: technology and instrument development, theoretical investigations of the possible signatures of habitable planets (through NASA's Astrobiology Institute), development of target star lists along with preparatory ground-based observations, execution and analysis of observing programs to search for and characterize planets using TPF, and General Observer programs for astrophysical imaging. The relative proportion of time TPF will spend on surveys of nearby stars, making spectroscopic follow-up observations of promising targets, and on astrophysical imaging will be made by a combination of NASA officals, a TPF science team selected by peer review around the start of the TPF implementation phase, and a community-based time allocation committee.

Programmatic Considerations

The Terrestrial Planet Finder mission described in this report has evolved over almost two decades of discussions within the scientific community and with various space agencies, as described in the Committee on Planetary and Lunar Exploration (COMPLEX), Towards Other Planetary Systems (TOPS), Darwin, and ExNPS reports. TPF is presently being considered by NASA for a new start in 2007 after the successful completion of key technological milestones during the development of the Space Interferometry Mission (SIM) and the Next Generation Space Telescope (NGST). . . .

The European Space Agency is presently studying the Infrared Space Interferometer (IRSI, formerly known as Darwin) for possible inclusion as a cornerstone mission in its Horizon 2000+ program. IRSI shares many of the scientific goals and technological challenges of TPF. Astronomers and engineers from both projects have established the groundwork for a fruitful collaboration on a project of broad public interest.

Additional information on TPF can be found at http://TPF.jpl.nasa.gov. *The relationship of TPF to NASA's overall Origins program is described on the Origins Web site*: http://Origins.jpl.nasa.gov.

The full report in pdf format entitled Terrestrial Planet Finder: Origins of Stars Planets and Life can be obtained at http://tpf.jpl.nasa.gov/library/tpf_book/index.html.

FUTURE ASTRONOMY: ASTROBIOLOGY

The following is an excerpt from the NASA Astrobiology Web site that lays out the "Roadmap" for astrobiology in the coming decades.

This roadmap was the result of a three-day workshop involving 100 participants held in 1998 at the NASA Ames Research Center. The potential to combine the skills of astronomers and biologists makes this an exciting field and one that is sure to be at the forefront of public interest in the coming decades.

Excerpt from NASA Astrobiology Web Site

INTRODUCTION

Astrobiology is the study of life in the universe. It provides a biological perspective to many areas of NASA research, linking such endeavors as the search for habitable planets, exploration missions to Mars and Europa, efforts to understand the origin of life, and planning for the future of life beyond Earth.

The NASA Astrobiology Roadmap is the product of efforts by more than 150 scientists and technologists, spanning a broad range of disciplines. More than 100 of these participated in a three-day Roadmap Workshop held in July 1998 at NASA Ames Research Center, while others attended previous topical workshops and are participating by email. The co-chairs of the Roadmap team are David Morrison, Director of Space at NASA Ames Research Center, and Michael Meyer, Astrobiology Discipline Scientist at NASA Headquarters and Program Scientist for Mars Sample Return. The Roadmap participants include NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the still wider community who have no formal association with NASA.

Astrobiology addresses three basic questions, which have been asked in some form for generations. Astrobiology is exciting today because we have the technology to begin to answer these fundamental questions:

Question: How does life begin and develop?

Question: Does life exist elsewhere in the universe?

Question: What is life's future on Earth and beyond?

The NASA Astrobiology Roadmap will provide guidance for research and technology development across several NASA Enterprises: Space Science, Earth Science, and the Human Exploration and Development of Space. The Roadmap is formulated in terms of ten Science Goals, and 17 more specific Science Objectives, which will be translated into specific programs and integrated with NASA strategic planning. In addition, the NASA Roadmap emphasizes four Principles that are integral to the operation of the Astrobiology Program.

[The following are the 10 Science Goals of the Astrobiology program and are expanded in detail under the broad questions listed in the Introduction.]

In order to answer the fundamental questions of astrobiology, the NASA Astrobiology program pursues the following science goals:

Question: How Does Life Begin and Develop?

Goal 1: Understand how life arose on the Earth.

Goal 2: Determine the general principles governing the organization of matter into living systems.

Goal 3: Explore how life evolves on the molecular, organism, and ecosystem levels.

Goal 4: Determine how the terrestrial biosphere has co-evolved with the Earth.

Question: Does Life Exist Elsewhere in the Universe?

Goal 5: Establish limits for life in environments that provide analogues for conditions on other worlds.

Goal 6: Determine what makes a planet habitable and how common these worlds are in the universe.

[As the Viking missions to Mars made clear, the following goal is extremely difficult and will occupy the minds of biologists and astronomers for some time to come.]

Goal 7: Determine how to recognize the signature of life on other worlds.

Goal 8: Determine whether there is (or once was) life elsewhere in our solar system, particularly on Mars and Europa.

Question: What Is Life's Future on Earth and Beyond?

Goal 9: Determine how ecosystems respond to environmental change on time-scales relevant to human life on Earth.

Goal 10: Understand the response of terrestrial life to conditions in space or on other planets.

[Finally, the following are the Principles of the Astrobiology program. These broad statements are proposed to serve as guiding principles to the endeavor of astrobiology in the coming decades. Whether these principles are too limiting, or are helpful in any way, only time will tell. It is interesting to note that the third principle strikes an almost religious tone in its appeal to ethics and stewardship. As astronomers enter the fray of questions about life, crossover discussions with philosophers, ethicists, and theologians will be inevitable and hopefully enlightening.]

In addition to goals and objectives, the NASA Roadmap emphasizes four operating principles that are integral to the Astrobiology Program.

> Principle 1: Astrobiology is multidisciplinary, and achieving our goals will require the cooperation of different scientific disciplines and programs.
>
> Principle 2: Astrobiology encourages planetary stewardship, through an emphasis on protection against biological contamination and recognition of the ethical issues surrounding the export of terrestrial life beyond Earth.
>
> Principle 3: Astrobiology recognizes a broad societal interest in our subject, especially in areas such as the search for extraterrestrial life and the potential to engineer new life forms adapted to live on other worlds.
>
> Principle 4: In view of the intrinsic excitement and wide public interest in our subject, Astrobiology includes a strong element of education and public outreach.

PROTECTING THE PLANET FROM ERRANT ASTEROIDS

A number of national organizations around the world have recognized the dangers and potential threat to life on Earth posed by a collision with a large asteroid. This potentially disastrous scenario has been portrayed in a number of movies, and despite the interest of Hollywood, there is valid concern about such an impact. The following excerpts are from the Report of the United Kingdom (UK) Task Force on Near Earth Objects (NEOs) published in September 2000. British spellings have been left unchanged in the first document. The entire document can be found at http://www.nearearthobjects.co.uk.

Excerpts from the Report of the United Kingdom (UK) Task Force on Near Earth Objects (NEOs)

EXECUTIVE SUMMARY

Enormous numbers of asteroids and comets orbit the Sun. Only a tiny fraction of them follow paths that bring them near the Earth. These Near Earth Objects range in size from pebbles to mountains, and travel at high speeds.

Such objects have collided with the Earth since its formation, and brought the carbon and water which made life possible. They have also caused widespread changes in the Earth's surface, and occasional extinctions of such living organisms as the dinosaurs.

The threat has only recently been recognised and accepted. This has come about through advances in telescope technology allowing the study of these usually faint objects, the identification of craters on the moon, other planets and the Earth as a result of impacts, and the dramatic collision of pieces of the comet Shoemaker-Levy 9 with Jupiter in 1994.

Impacts represent a significant risk to human and other forms of life. Means now exist to mitigate the consequences of such impacts for the human species.

The largest uncertainty in risk analysis arises from our incomplete knowledge of asteroids whose orbits bring them near to the Earth. With greater information about them, fairly accurate predictions can be made. The risk from comets is between 10 and 30 per cent of that from asteroids. The advance warning period for a potential impact from a long period comet may be as short as a year compared to decades or centuries for asteroids. Short period comets can be considered along with asteroids.

The threat from Near Earth Objects raises major issues, among them the inadequacy of current knowledge, confirmation of hazard after initial observation, disaster management (if the worst came to the worst), methods of mitigation including deflection, and reliable communication with the public. The Task Force believes that steps should be taken at government level to set in place appropriate bodies—international, European including national—where these issues can be discussed and decisions taken. The United Kingdom is well placed to make a significant contribution to what should be a global effort.

[The following segment from the same report makes recommendations about the effort of the United Kingdom as well as the role of the United Kingdom in an international effort.]

SUMMARY OF RECOMMENDATIONS

Recommendations 1 to 9 cover the United Kingdom's scientific role within an international effort and Recommendations 10 to 14 the coordination of all aspects of the subject internationally, in Europe and in Britain.

SURVEY AND DISCOVERY OF NEAR EARTH OBJECTS

Recommendation 1

We recommend that the Government should seek partners, preferably in Europe, to build in the southern hemisphere an advanced new 3 metre-class survey telescope for surveying substantially smaller objects than those now systematically observed by other telescopes. The telescope should be dedicated to work on Near Earth Objects and be located on an appropriate site.

Recommendation 2

We recommend that arrangements be made for observational data obtained for other purposes by wide-field facilities, such as the new British VISTA [Visible and Infrared Survey Telescope for Astronomy] telescope, to be searched for Near Earth Objects on a nightly basis.

Recommendation 3

We recommend that the Government draw the attention of the European Space Agency to the particular role that GAIA, one of its future missions, could play in surveying the sky for Near Earth Objects. The potential in GAIA, and in other space missions such as NASA's SIRTF and the European Space Agency's BepiColombo, for Near Earth Object research should be considered as a factor in defining the missions and in scheduling their completion.

ACCURATE ORBIT DETERMINATION

Recommendation 4

We recommend that the 1 metre Johannes Kapteyn Telescope on La Palma, in which the United Kingdom is a partner, be dedicated to follow-up observations of Near Earth Objects.

COMPOSITION AND GROSS PROPERTIES

Recommendation 5

We recommend that negotiations take place with the partners with whom the United Kingdom shares suitable telescopes to establish an arrangement for small amounts of time to be provided under appropriate financial terms for spectroscopic follow-up of Near Earth Objects.

Recommendation 6

We recommend that the Government explore, with like-minded countries, the case for mounting a number of coordinated space rendezvous missions based on relatively inexpensive microsatellites, each to visit a different type of Near Earth Object to establish its detailed characteristics.

COORDINATION OF ASTRONOMICAL OBSERVATIONS

Recommendation 7

We recommend that the Government—together with other governments, the International Astronomical Union and other interested parties—seek ways of putting the governance and funding of the Minor Planet Center on a robust international footing, including the Center's links to executive agencies if a potential threat were found.

STUDIES OF IMPACTS AND ENVIRONMENTAL AND SOCIAL EFFECTS

Recommendation 8

We recommend that the Government should help promote multi-disciplinary studies of the consequences of impacts from Near Earth Objects on the Earth in British and European institutions concerned, including the Research Councils, universities and the European Science Foundation.

MITIGATION POSSIBILITIES

Recommendation 9

We recommend that the Government, with other governments, set in hand studies to look into the practical possibilities of mitigating the results of impact and deflecting incoming objects.

ORGANISATION INTERNATIONALLY

Recommendation 10

We recommend that the Government urgently seek with other governments and international bodies (in particular the International Astronomical Union) to establish a forum for open discussion of the scientific aspects of Near Earth Objects, and a forum for international action. Preferably these should be brought together in an international body. It might have some analogy with the Intergovernmental Panel on Climate Change, thereby covering science, impacts, and mitigation.

ORGANISATION IN EUROPE

Recommendation 11

We recommend that the Government discuss with like-minded European governments how Europe could best contribute to international efforts to cope with Near Earth Objects, coordinate activities in Europe, and work towards becoming a partner with the United States, with complementary roles in specific areas. We recommend that the European Space Agency and the European Southern Observatory, with the European Union and the European Science Foundation, work out a strategy for this purpose in time for discussion at the ministerial meeting of the European Space Agency in 2001.

ORGANISATION IN UNITED KINGDOM

Recommendation 12

We recommend that the Government appoint a single department to take the lead for coordination and conduct of policy on Near Earth Objects, supported by the necessary interdepartmental machinery.

BRITISH NATIONAL CENTRE FOR NEAR EARTH OBJECTS

[The British government responded to the report in the early part of 2001 but has not as yet called for the establishment of a center as proposed below.]

Recommendation 13

We recommend that a British Centre for Near Earth Objects be set up whose mission would be to promote and coordinate work on the subject in Britain; to provide an advisory service to the Government, other relevant authorities, the public and the media, and to facilitate British involvement in international activities. In doing so it would call on the Research Councils involved, in particular the Particle Physics and Astronomy Research Council and the Natural Environment Research Council, and on universities, observatories and other bodies concerned in Britain.

Recommendation 14

We recommend that one of the most important functions of a British Centre for Near Earth Objects be to provide a public service which would give balanced information in clear, direct and comprehensible language as need might arise. Such a service must respond to very different audiences: on the one hand Parliament, the general public and the media; and on the other the academic, scientific and environmental communities. In all of this, full use should be made of the Internet. As a first step, the Task Force recommends that a feasibility study be established to determine the functions, terms of reference and funding for such a Centre.

[The Web site http://impact.arc.nasa.gov contains links to a number of reports on the international effort to track and catalog near-earth objects. The following is a news item from the archive discussing current efforts being made in Russia.]

News Archive: 2000—Russian NEO Status: Reports on Studies in Russia on Protection of the Earth from NEO Impacts

INTRODUCTION

Following are reports on the status of the Russian efforts toward planetary defense. The information has been communicated by Vadim Simonenko and Anatoly Zaitsev of the Russian Federal Nuclear Center at Snezhinsk (Chelyabinsk-70). It is primarily the results of three meetings of the Space Protection of the Earth conference, the most recent of which was held in September 2000. . . .

INTERNATIONAL CONFERENCE ON SPACE PROTECTION OF THE EARTH, EVPATORIA, UKRAINE, 11–15 SEPTEMBER 2000

Memorandum of the Conference, supplied by Vadim A. Simonenko

During the last decades, many studies have shown that at this stage of solar system evolution, considerable danger still exists from close encounters of Earth with minor space bodies: asteroids, comets and their fragments. Impacts from such bodies could cause local, regional or global catastrophes. Global catastrophes occur once every 100,000 to one million years; these are the most dangerous, with consequences ranging from degradation of the human race to its total elimination. Regional events, such as tsunamis caused by falls of large bodies into the oceans, have higher frequencies (1 every 10,000–100,000 years); they may cause the death of up to hundreds of millions of people and huge economical losses. Even local events, like the Tunguska explosion, may represent a severe threat. Such an event occurring over a large city causes the death of several million people and an economic loss comparable with the gross national product of some industrialized countries. These events occur about once every 100–300 years.

For the first time in history, we have reached a sufficiently high level of technology to cope with the danger, by finding the hazardous objects in space and by adopting measures able to prevent space impacts. The unanswered question is whether we, as a global society, are ready and willing to provide the resources necessary to preserve our safety, or whether we will postpone such a decision until the next disaster actually happens.

The inventory of dangerous objects is far from complete. Large asteroids with sizes greater than 1 km pose the greatest threat and are mostly visible from ground; in the last years their discovery rate has increased thanks to the efforts of researchers in the USA, but an international program must be put in place to monitor and study them. It is believed that about 50% of the population of largest objects has been discovered; this is expected to reach 90% completeness by 2010. However, it is desirable to implement an extended, international program for their physical characterization, including possible space reconnaissance missions. The gathering of all necessary information will give the opportunity to make appropriate decisions about the methods and technologies we might use to prevent the largest impacts.

The situation is more complex with regard to smaller objects. The number of medium-size objects (between 100 meters and 1 km) is evaluated to be around 100,000–200,000 and it is difficult, if not impossible, to catalogue them all using current technology. In order to prevent impacts from such objects another strategy should be used. We should identify those objects that are on a collision course with the Earth and mitigation technology should neutralize them when they approach the Earth within several million kilometers or less. To provide reliable and timely discovery of such objects it is necessary to have [a] network of two or more ground-based middle-size large-field telescopes and one or two space-based ones. Ground-based radio locators could provide precise trajectory measurements. It is also important to develop exploratory missions for such objects to study their physical properties. The missions would represent the prototypes of future technological means for impact mitigation.

The participants to the Conference recommend to the Science Academies of Russia and Ukraine, the Russian and Ukrainian Space Agencies, the Russian Ministries for Atomic Energy, and for Extreme Situations to plan a national program of investigation into the hazards posed by impacts and develop systems for their mitigation.

The Conference also recommends that international efforts be coordinated along the aforementioned research lines, and international programs be created to discover, monitor, and explore these dangerous objects, in order to develop an impact prediction, mitigation strategies and technology.

[Finally follows the report of Dr. Carl Pilcher, science director, Solar System Exploration, Office of Space Science, NASA, to Congress that was made in 1998 during the congressional hearings on near-Earth objects. This report summarizes the issues involved and the status of the NASA-funded efforts.]

U.S. Congressional Hearings on Near-Earth Objects and Planetary Defense, May 21, 1998: Statement of Dr. Carl Pilcher

BACKGROUND

This Committee has been a leader in focusing attention on the importance of cataloging and characterizing Earth-approaching asteroids and comets. In 1992, the Committee on Science directed that NASA sponsor two workshop studies, the NEO Detection Workshop, which was chaired by NASA, and the NEO Interception Workshop, which was chaired by the Department of Energy. In March 1993, the Science Committee held a hearing to review the results of these two workshops. In 1995, at the Committee's request, NASA conducted a follow-up study which was chaired by the late Dr. Gene Shoemaker. Each of these studies stressed the importance of characterizing and cataloging NEOs with diameters larger than 1 km within the next decade. We have taken steps to put us on a path to achieving this goal. I am here today to tell you about those steps, as well as to bring you up to date on the rich program of space missions to NEOs and related objects.

The NEO population is derived from a variety of scientifically interesting sources including planetesimal fragments and some Kuiper belt objects. Indeed, the Office of Space Science Strategic Plan includes as a specific goal ". . . to complete the inventory and characterize a sample of Near Earth Objects down to 1 km diameter." While the threat of a catastrophic collision is statistically small, NASA has a vigorous program of exploration of NEOs planned, including both asteroids and comets.

There has been much recent discussion about the potential threat posed by NEOs, but NASA has long been interested in them from a scientific standpoint. NEO investigations have had to compete for support against a number of other compelling science programs; funding selection criteria were based principally on scientific merit. This approach has led to the detection of over 400 NEOs, including more than 100 objects larger than 1 km, and to a rapid advancement of the technologies necessary for NEO detection. In fact, this research effort has demonstrated that we can inventory the NEO population in a reasonable time, about a decade, with an achievable increase in funding from recent levels.

A little less than a year ago, NASA initiated a study of its existing NEO research to determine how well we were doing in terms of reaching our goal of inventorying the population of NEOs larger than 1 km and characterizing a sample of them. While we have made some impressive strides, it became apparent that the funding levels resulting from scientific competitive review

($1–1.5 M per year) was not sufficient to accomplish our goal. The detection of new NEOs in 1997, the last year for which we have statistics, is barely 10% of the rate needed to achieve the goal suggested in the Shoemaker report (detection of 90% of the NEO population larger than 1 km within a decade). In simple terms, we need to survey about 20,000 square degrees of sky a month for NEOs to a limiting brightness of approximately 20th magnitude to accomplish the inventory. To understand what this means, note that 20,000 square degrees is about half the sky and that magnitudes are a measure of apparent brightness—a 6th magnitude object is at the limit of detection for the human eye and 20th magnitude is almost 100,000 times fainter.

I would now like to describe briefly the existing search programs, NASA's plans to improve them, and some promising new research programs which we are considering. I will also comment on our joint activities with the Air Force Space Command. All of these efforts are directed toward increasing the rate of discovery of NEOs in order to reach our goal.

STATUS OF ONGOING SEARCH PROGRAMS

NASA's ground-based NEO program comprises three parts: Spacewatch, the Near-Earth Asteroid Tracking (NEAT) program, and the Lowell Near Earth Asteroid Survey (LONEOS [Lowell Observatory Near-Earth Object Search]).

SPACEWATCH

Spacewatch is a program at the University of Arizona, led by Dr. Tom Gehrels, which has done much of the pioneering work in the field of NEO detection. This group is responsible for more NEO discoveries than any other. The current Spacewatch Program searches 200 square degrees of sky per month to a depth of 21st magnitude. This year NASA is funding a new state-of-the-art focal plane camera for Spacewatch, which will lead to an 8-fold increase in the area of sky that they search each month (to 1600 square degrees per month). We hope in the future to assist them in their efforts to bring their new 1.8 m telescope on line. This telescope will enable them to detect even fainter NEOs.

NEAT

NEAT is a program headed by Dr. Eleanor Helin at the Jet Propulsion Laboratory. NEAT uses a specialized camera, which is based on a 4096 × 4096 CCD array for use on the 1 m GEODSS (Ground-Based Electro-Optical Deep Space Surveillance) telescope, operated by United States Air Force

Space Command (USAFSC) on Haleakala, Maui, Hawaii. This group is currently limited by the number of nights per month on which they can observe the sky using the GEODSS system. They are presently observing six nights per month on one of the seven GEODSS telescopes. With recent improvements they are now able to search 800 square degrees per night (4800 square degrees per month) to about 20th magnitude. We have funded the construction of 2 more cameras, which we hope to install on two other GEODSS telescopes. This increase in the level of effort for NEO detection is being discussed in the NASA-USAFSC Partnership Council co-chaired by NASA Administrator Daniel Goldin and AFSC Commander Gen. Howell Estes. It is in principle possible to scan 21,000 square degrees a month with three cameras and full access to three of the GEODSS telescopes. It is important to note that the GEODSS system includes one southern hemisphere site.

While we certainly hope to increase our surveying ability using the GEODSS system, we are aware that it has other vital missions. NASA's FY 1999 budget request includes sufficient funding for the construction of four more NEAT cameras, which will enable us to equip all seven GEODSS telescopes. The final application of the funds will depend on the demonstration that the NEAT camera can support the existing mission of the GEODSS system as well as the search for NEOs. This matter is currently being reviewed by the Partnership Council on NEOs.

LONEOS

LONEOS is led by Dr. Ted Bowell at Lowell Observatory in Flagstaff, Arizona. This group has great potential (capability to observe 4,300 square degrees a month down to 20th magnitude); however, they have not yet reached this level of performance. We are funding an augmentation to buy a second focal plane CCD and to support additional software development in order to allow them to reach their performance objective.

New Search Programs

The increased interest in the search for NEOs has led to several recent proposals from new groups:

CATALINA NEO SURVEY

We are supporting a new search program at the University of Arizona, which is headed by Mr. Steven Larson, to refurbish an existing telescope on Mount Lemon. When fully operational, this system will survey 8,000 square degrees of sky per month to a depth of 19th magnitude. This program will be fully operational within a year.

LINEAR

NASA is evaluating a proposal for support of a very promising search program from the MIT Lincoln Labs. This effort called LINEAR (Lincoln Near Earth Asteroid Research program) uses a state-of-the-art camera which was developed as a possible prototype for the next generation GEODSS detector. They are proposing to use a 1 m telescope at their Experimental Test Site near Socorro, New Mexico, to survey 10,000 square degrees down to 21st magnitude each month.

With coordination of these different observational programs, NASA believes it is possible to obtain the level of sky coverage to the appropriate limiting magnitude required to complete the survey. NASA has already committed over $3M this year, much of it to fund improvements to focal plane detectors, software, and electronics. NASA is committed to funding both existing and new search programs at, at least, the FY 1998 level. We believe this is close to the level required to achieve our objective.

Space-Based Missions Relevant to Our Understanding of NEOs

The study of the physical characteristics of NEOs is a major focus of both ground-based research and space missions. The ground-based work includes NASA-supported radar imaging of NEOs utilizing the Arecibo Radio Telescope and spectroscopy of NEOs from optical/IR [infrared] telescopes to determine their composition.

Several NASA missions will travel to asteroids and/or comets to provide us with exciting new scientific insights about these objects; at the same time this information is valuable for any future effort to respond to an impact threat. Over the next decade NASA will invest approximately $1B in these missions. Missions in flight or in development are:

> NEAR [Near Earth Asteroid Rendezvous], which will reach the near-Earth object Eros in January, 1999, orbit for one year to measure its surface and interior properties, and then land on Eros.
>
> CONTOUR [Comet Nucleus Tour], which will fly by a set of three short-period comets and make the first detailed comparative study of cometary nuclei.
>
> STARDUST, which will return a sample from the coma of short-period comet in 2006.
>
> ROSETTA, is a European Space Agency (ESA) mission to comet P/Wirtanen. NASA is providing three ROSETTA orbiter instruments and support to eight U.S. co-investigators on other orbiter instruments.

Missions soon to enter development are:

MUSES-C/N with Japan to deploy a US-provided micro-rover on the surface of an NEO and to return a sample of the asteroid to Earth in 2006.

DS [Deep Space]-4/Champollion to land on a comet, measure its composition, test sampling and sample-return technologies for small bodies, and perhaps even return a sample.

Pluto/Kuiper Belt Express to survey one or more Kuiper belt objects before deflection into the inner solar system.

Concluding Remarks

The issues and challenges posed by NEOs are inherently international, and any comprehensive approach to addressing them must be international as well. Central areas of concern include coordination among NEO observers and orbit calculators around the globe and public notification should an object posing a significant hazard to Earth be discovered. NASA has begun discussing, with the international community, convening an international workshop to address these issues. The goal of this workshop will be to develop international procedures and lines of communication to ensure that the best available accurate information about any potentially hazardous object is assembled and disseminated to the public in the shortest possible time.

To facilitate coordination among NASA-supported researchers, other agencies and scientists, and the international community, NASA is establishing an NEO Program Office. This Office will coordinate ground-based observations, ensure that calculated orbital elements for NEOs are based on the best available data and support NASA Headquarters in the continuing development of strategies for the exploration and characterization of NEOs. In the unlikely event that a potentially hazardous object is detected, the Office would coordinate the notification of both the observing community and the public of any potentially hazardous objects discovered.

NASA is committed to achieving the goal of detecting and cataloging 90% of NEOs larger than 1 km in diameter within 10 years, and to characterizing a sample of these objects. We are developing and building instruments, and developing partnerships—particularly with the Air Force—which should lead to the necessary detection and cataloging capability being in place in 1–2 years. This capability will also allow us to detect and characterize many NEOs smaller than 1 km.

In summary, NASA's obligation and commitment is to ensure that we have the information necessary to understand the hazards posed by NEOs.

The previous document was obtained from the NASA Ames Space Science Division Asteroid and Comet Impact Hazards Internet site news archive (http://impact.arc.nasa.gov/).

Chapter Five

Biographical Portraits

This chapter provides a sampling of biographical sketches from the fields of theoretical, observational, and amateur astronomy. The following pages include portraits of many of the investigators responsible for the science mentioned in the first two chapters, as well as others not mentioned elsewhere in the book. As in other chapters of this book, a chapter of about 40 biographies in the field can never be exhaustive or complete but can hopefully be representative.

To present as complete a picture of the field as possible, we have included astronomers at all points in their careers, including college faculty, scientists at national observatories, graduate students, and undergraduates. We also have included biographies of a number of amateur astronomers, some of whose goals are primarily related to public outreach and others whose observations provide research-quality data for professional colleagues. These brief summaries indicate the broad range of interest and dedication that astronomers have brought to their careers.

Alan P. Boss

Alan P. Boss, research scientist at the Carnegie Institution of Washington's Department of Terrestrial Magnetism (DTM), holds three degrees in theoretical physics, including an M.A (1975) and Ph.D. (1979) from the University of California, Santa Barbara. Following two years as a National Academy of Sciences/National Research Council Fellow at the NASA Ames Research Center in California, in 1981 he joined DTM's planet formation group and extended DTM's research program to include the formation of stars as well as planets.

For the last two decades, Boss has been a prolific contributor to the professional scientific literature on star and planet formation, having published hundreds of research papers, abstracts, reports, and letters. Boss is well known as one of the world's leading authorities on the formation of stars and planets. He has worked extensively on an astrophysical theory known as the fragmentation mechanism, which is the leading explanation for the formation of binary stars.

Beginning in 1988, Boss served on the primary committee advising NASA about how best to search for extrasolar planets, becoming chairman of the committee in 1995. Dr. Boss has served on numerous other committees for NASA and the National Academy of Sciences and authored the science justification sections for key reports dealing with planet detection. He is the author of the trade book *Looking for Earths: The Race to Find New Solar Systems* (John Wiley and Sons, 1998).

Allan S. Brun

Dr. Brun received his Ph.D. in astronomy in 1998 from the Observatory of Paris, Meudon. In January 1999, he moved to the Joint Institute of Laboratory Astrophysics (JILA) at the University of Colorado, Boulder, to become a research associate.

His interests concentrate mainly in *helioseismology* and solar neutrino problem; in particular, Brun carries out the computation of models of the interior structure of the sun. Brun has worked to improve the physical description of such models by introducing the most up-to-date nuclear and atomic data as well as macroscopic processes, including turbulent pressure, and mixing in the core of the sun. Brun is a member of the Global Oscillations at Low Frequency (GOLF) interpretation team of the Solar and Heliospheric Observatory (SOHO). This team is investigating the internal structure of the sun as revealed by low-frequency oscillations that the satellite can detect.

Geoffrey Burbidge

Dr. Burbidge attended the University of Bristol and the University of London (Ph.D. 1951). Since that time, Burbidge has held positions at Cambridge University, the California Institute of Technology, and Yerkes Observatory. Since 1962, he has been on the faculty of the University of California, San Diego. He served as director of the Kitt Peak National Observatory (KPNO) for six years.

His research has focused on non–thermal radiation processes, galactic structure, and mass of galaxies. In perhaps his most significant contribution to astronomical understanding (1957), he collaborated with his wife Margaret Burbidge, William A. Fowler, and Fred Hoyle to propose that the elements of the periodic table are produced by fusion reactions in the cores of stars. Since 1974 Burbidge has been an editor of the *Annual Reviews of Astronomy and Astrophysics.*

Margaret Burbidge

Born Eleanor Margaret Peachey, Margaret Burbidge completed undergraduate work in physics at the University of London in 1948. She subsequently joined the staff of the University of London Observatory, where she later received her Ph.D. and served as acting director. She has held positions at Yerkes Observatory, the Cavendish Laboratory, and the California Institute of Technology. Since 1964, Burbidge has been professor of astronomy at the University of California, San Diego, and has served as director of the Center for Astrophysics and Space Sciences. For a brief time she served as director of the Royal Greenwich Observatory.

In addition to collaborating on the seminal 1957 paper on nucleosynthesis in stars (see entry on Geoffrey Burbidge), Margaret Burbidge has published widely on the nature of quasars since 1967. She continues to investigate the nature of quasars and other high energy phenomena. Margaret Burbidge is the wife of Geoffrey Burbidge.

Alan Calder

Alan Calder is a research associate at the Center for Astrophysical Thermonuclear Flashes at the University of Chicago. He completed his graduate studies and received his Ph.D. in physics from Vanderbilt University in August 1997. His dissertation research investigates the role of convection in core collapse supernovae using multidimensional hydrodynamics coupled to multigroup neutrino transport. His dissertation research was performed at Oak Ridge National Lab (ORNL) in the Physics Division.

Dr. Calder's research focuses largely on supernovae, the violent explosions that signal the death of a massive star. Galactic supernovae occur infrequently on a human time scale. So, rather than waiting for the next supernova to occur, Dr. Calder works to make progress by simulation, and by studying the observed abundances of various elements in the Universe.

Bernard Carr

Bernard Carr studied mathematics as an undergraduate at Trinity College, Cambridge, and for his Ph.D he studied the first second of the universe, working under Stephen Hawking. His thesis work focused particularly on the formation and evaporation of primordial black holes. Carr was elected to a Fellowship at Trinity College and then spent a year traveling around America as a Lindemann Fellow, based at the California Institute of Technology and Berkeley, before taking up a Senior Research Fellowship at the Institute of Astronomy in Cambridge. In 1985 he moved to the University of London, where he is now professor of mathematics and astronomy at Queen Mary & Westfield College. He has held visiting professorships at various institutes in North America and Japan.

Carr's main area of research is cosmology and relativistic astrophysics, with particular interest in such topics as the early universe, dark matter, Population III (primordial) stars, gravitational lenses, black holes, gravitational waves, cosmological solutions to Einstein's equations, and the *anthropic principle.*

Roger A. Chevalier

Roger Chevalier is a theoretical astrophysicist at the University of Virginia, where he is the W.H. Vanderbilt Professor of Astronomy. He was an astronomer at Kitt Peak National Observatory before becoming an associate professor at the University of Virginia in 1979, where he has been since.

Dr. Chevalier's research is in the area of theoretical astrophysics, in particular supernovae and their interaction with their environments. Chevalier is a member of the National Academy of Sciences and has served on many professional committees, most recently the Committee on Astronomy and Astrophysics (1997–1999).

Hélène R. Dickel

Dr. Hélène R. Dickel received her A.B. in mathematics from Mount Holyoke College in 1959 and her Ph.D. in astronomy from the University of Michigan in 1964. She is currently a research professor of astronomy at the University of Illinois. Professor Dickel is chair of the Commission 5 Task Group on Astronomical Designations of the International Astronomical Union and was recently elected a member of the scientific organizing committee of (IAU) (International Astronomical Union) Commission 40 on Radio Astronomy.

She codiscovered the first formaldehyde maser in 1979 and is a pioneer in radio molecular spectroscopy using radio aperture synthesis techniques, including making some of the first images of molecular distributions with the Westerbork Synthesis Radio Telescope in the Netherlands, the Very Large Array of radio telescopes of the National Radio Astronomy Observatory, and the millimeter array of the Berkeley Illinois Maryland Association for which she was the BIMA scheduler from 1994 through 1998 and continues to maintain the BIMA observing statistics. She is the author of nearly 100 publications, most recently concentrating on radiative transfer modeling of star-forming regions.

Andrea Dupree

Dr. Dupree earned her B.A. in astronomy and physics in 1960 from Wellesley College and her Ph.D. in astrophysics from Harvard in 1968.

Dr. Dupree has served as president of the American Astronomical Society, and is currently a senior astrophysicist at the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts, and an astronomy lecturer at Harvard. In 1980, she was appointed as associate director of the CfA and was the first woman and the youngest person ever named to the position. She served as associate director until 1987. Her scientific research is focused on observations of stars and the theory of stellar evolution. In 1995, Dupree made the first observations of a stellar surface in the ultraviolet (Betelgeuse). Since then, Dupree and collaborators have been monitoring the ultraviolet emission from the atmospheres of a number of stars with the Hubble Space Telescope.

Sandra Faber

Dr. Faber received her B.A. from Swarthmore College and her Ph.D. from Harvard University in 1972. Faber is currently a professor of astronomy at the University of California, Santa Cruz. She is a member of the National Academy of Sciences and the American Academy of Arts and Sciences.

Among her many professional accomplishments, Faber is discoverer of the “Faber-Jackson relation,” a correlation that indicates a relationship between the brightness of elliptical galaxies and the speeds of stars orbiting within them. This relation has been an important rung in the *distance ladder* that astronomers use to gauge the distances between galaxies in the universe. She also participated in the construction of two of the largest optical telescopes in the world, the two 10-m Keck Telescopes in Mauna Kea, Hawaii. She has been a frequent observer with the Hubble Space Telescope (HST), and uses her time to observe galactic centers and massive black holes.

Debra Fischer

Debra Fischer received her Ph. D. in astronomy from the University of California at Santa Cruz in 1998. She is currently a postdoctoral fellow at UC Berkeley.

Fischer is a member of the team of astronomers based at UC Berkeley deeply engaged in the extrasolar planet search begun by Geoff Marcy and Paul Butler. As part of her research, she gathers spectral line data from over 400 stars using the telescopes of the Lick Observatory. These data have provided and continue to provide evidence for the presence of planetary companions around other stars.

Wendy Freedman

Dr. Freedman is a native of Canada and earned her Ph.D. in astronomy and astrophysics from the University of Toronto in 1984. She was subsequently a recipient of a Carnegie Fellowship at the Carnegie Observatories in Pasadena, California, in 1984. She joined the faculty there in 1987 and has remained since.

Much of her research is focused on measuring the value of the rate of expansion of the universe. In 1994, Dr. Freedman was awarded the Marc Aaronson Lectureship and prize as a result of her fundamental work on the extragalactic distance scale and the stellar populations of galaxies. Dr. Freedman is a member of the National Academy of Sciences/National Research Council Committee on Astronomy and Astrophysics and of the scientific oversight committee for the Next Generation Space Telescope (NGST), described in Chapter 2.

Tom Gehrels

Dr. Tom Gehrels received his Ph.D. from the University of Chicago in 1956 and is currently a professor of solar system astronomy at the Lunar and Planetary Lab (LPL) of the University of Arizona.

Dr. Gehrels is cofounder of Spacewatch (along with Dr. Robert S. McMillan, who now leads the project). The goal of Spacewatch is to discover and study the population of small objects in the solar system. The project operates 0.9-m and 1.8-m telescopes on Kitt Peak near Tucson, Arizona. The Spacewatch project has had many successes and firsts, including the first Near Earth Asteroid (NEA) discovered with a CCD in 1989, pioneering the use of CCD-scanning and automated detection of moving objects. The 0.9-meter Spacewatch Telescope routinely finds 20,000 moving objects each year, about 20 to 30 of which are NEAs. Dr. Gehrels is also the general editor of the *Space Science* Series of the University of Arizona Press.

Robert Douglas Gehrz

Dr. Gehrz received his B.A. in physics from the University of Minnesota in 1967 and his Ph.D. in physics from the University of Minnesota in 1971. He is currently professor of physics and astronomy at the University of Minnesota and adjunct professor of physics and astronomy at the University of Wyoming.

Among his many accomplishments, Gehrz collaborated to design and construct the Wyoming Infrared Telescope, which was the largest telescope of its kind when it was completed in 1977. Gehrz and collaborators have developed an advanced computer-operated control system that enables them to remotely control three infrared telescopes from their laboratory at the University of Minnesota. Using infrared technologies and telescopes, Gehrz participated in the discovery of silicate emission from Ic Variables, the discovery of excess infrared radiation from RV Tauri stars, the discovery of strong thermal emission from cold dust in WC9 stars, the discovery of a new class of infrared novae that show strong forbidden line emission from neon, and many other observations.

Gehrz is a member of the American Astronomical Society, the International Astronomical Union, and other professional societies; he is also a Fellow of the Royal Astronomical Society. Gehrz is currently Chairman of the NASA Infrared and Radio Astrophysics Management Operations Working Groups, and a member of the NASA Astrophysics Science Advisory Committee. Gehrz recently served as President of the American Astronomical Society.

Andrea Ghez

Dr. Andrea Ghez earned her bachelor's degree in physics from Massachusetts Institute of Technology in 1987 and her Ph.D. from California Institute of Technology in 1992. She is the recipient of numerous honors and awards, including the Annie Jump Cannon Award, a

Sloan Fellowship, a Hubble Postdoctoral Research Fellowship at the Steward Observatory of the University of Arizona, and the National Science Foundation's Young Investigator award. Dr. Ghez is now a professor of physics and astronomy at the University of California, Los Angeles.

Ghez observes with a number of different telescopes, primarily at infrared wavelengths. Her research interests include the development and application of high spatial resolution infrared imaging techniques. Dr. Ghez's research has been primarily in two areas: (1) the origin and early evolution of stars and planets and (2) the distribution of matter at the galactic center and the possible existence there of a supermassive black hole.

Deborah Haarsma

Dr. Deborah Haarsma is an assistant professor in the Department of Physics & Astronomy at Calvin College, a Christian liberal arts college in Grand Rapids, Michigan. She attended Bethel College in St. Paul and graduated in 1991 with a B.S. in Physics and a Bachelor in Music in Piano Performance. She entered the graduate astrophysics program at the Massachusetts Institute of Technology, and completed a Ph.D. in physics in 1997. For the next two years, she did postdoctoral work at Haverford College in Philadelphia, and has been at Calvin since 1999.

Haarsma's research interests are in galaxies and the universe as a whole, and what can be learned about them at radio wavelengths. Most of her work has been in the area of *gravitational lensing*, a phenomenon of general relativity in which light is bent by gravitational fields, distorting and multiplying the images of distant galaxies. Gravitational lenses can increase our understanding of the expansion rate of the universe, its mass density, and the cosmological constant, which in turn determine the age and curvature of the universe, as well as whether it will expand forever or ultimately collapse. Other scholarly interests include the physics of musical instruments and the intersection of science and faith.

Michael Kramer

Kramer was born in Cologne, Germany. He carried out his undergraduate studies in physics at the University of Cologne, Germany, before moving to the University of Bonn for a graduate course in astronomy. He obtained his Ph.D. in astronomy in December 1995.

Since 1999, when he accepted a lectureship position in physics and astronomy at the University of Manchester, United Kingdom, he has been working at the Jodrell Bank Observatory.

Michael Kramer's research interests mainly focus on pulsar astronomy. Using the 100-m radiotelescope in Effelsberg and the 30-m millimeter radiotescope on Pico Veleta, he performed the first mm-observations of pulsars. His area of research also covers pulsar searches, pulsar timing, the emission physics of pulsars and in particular the many interesting topics related to recycled, millisecond pulsars.

Cornelia Lang

Dr. Lang is currently a postdoctoral fellow in the Five College Astronomy Department at the University of Massachusetts, Amherst. She received her B.A. from Vassar College in Poughkeepsie, New York, where she majored in astronomy and physics and also studied Ancient Greek and Latin. Her Ph.D. in astronomy (2000) is from the University of California at Los Angeles. Her thesis work focused on understanding the complex interstellar environment at the center of the Milky Way galaxy. Cornelia spent the final two years of her Ph.D. at the Very Large Array (VLA) in New Mexico, making observations of the hot gas and magnetic fields at the galactic center. At the University of Massachusetts Dr. Lang is expanding her view of the center of the Milky Way by probing the hottest and most energetic interstellar sources using the Chandra X-ray Satellite to make comparisons with radio observations and construct a multi-wavelength picture of our galactic center.

Lang has a strong interest in teaching and in science education. She also organizes bimonthly lunch meetings of a group of women scientists at the University of Massachusetts ("Women in Science and Engineering," or WISE) from across the physical science disciplines who meet to discuss their personal and professional experiences as scientists.

Geoffrey W. Marcy

Marcy received his B.A. in physics and astronomy from the University of California at Los Angeles (UCLA) in 1976 and his Ph.D. from the University of California Santa Cruz in 1982. Marcy was a Carnegie Fellow from 1982 to 1984, a professor of physics and astronomy at San Francisco State University from 1984 to 1996, and has been a professor of astronomy at the University of California at Berkeley since 1999.

Dr. Marcy's research has focused on the detection of extrasolar planets and brown dwarfs. His team has discovered several dozen extrasolar planets, allowing study of their masses, radii, and orbits. Among the planets discovered is the first multiple-planet system, the first Saturn candidates, and the first transiting planet. Ongoing work is designed to study the mass distribution of planets and the eccentricity of their orbits. His five-year goal is to find Jupiter analogs located about 5 AU from their host star. Dr. Marcy is participating in the University of California at Berkeley's new Center for Integrative Planetary Science, designed to study the formation, geophysics, chemistry, and evolution of planets.

Janet Mattei

Janet Akyuz Mattei (a native of Turkey) earned her B.A. at Brandeis, M.S. in astronomy at Ege University (Turkey) and the University of Virginia, and her Ph.D. in astronomy at Ege University. Mattei is widely recognized for her accomplishments in the field of variable star observing and has served as director of the American Association of Variable Star Observers (AAVSO) since 1973. Mattei is a member of the Hubble Space Telescope (HST) Amateur Astronomers Working Group, a body charged with selecting amateur astronomy projects for observations with the HST.

As AAVSO director—a global effort—Mattei must oversee the analysis of more than 300,000 observations annually from variable star observers. Since 1973, she has provided results and analysis from the variable star database for more than 700 research projects. She has served on numerous committees and working groups, and in 1993, she received both the George Van Biesbroeck Award and the Leslie Peltier Award for her role in the success of the AAVSO.

Michel Mayor

Dr. Mayor is a Swiss citizen and a professor in the Department of Astronomy at the University of Geneva. He has been the director of the Geneva Observatory since 1998.

Dr. Mayor is most famous for his co-discovery (along with Didier Queloz) of the first extrasolar planet orbiting 51 Pegasus in 1995. He is also the recipient of many awards, including the 1998 Marcel-Benoist Prize awarded by the Swiss Confederation and the 1998 Janssen Prize awarded by the Astronomical Society of France.

David Morrison

Dr. Morrison received his Ph.D. in astronomy from Harvard University. Following receipt of his Ph.D., he served as a professor of astronomy at the University of Hawaii until he joined NASA.

Currently the director of Astrobiology and Space Research at NASA Ames Research Center, Dr. Morrison oversees the NASA research programs in space, life, and Earth science, all of which fall under the broad category of astrobiology. Dr. Morrison served as cochair of the Roadmap Team that organized the NASA Astrobiology Roadmap Workshop in 1998. Internationally known for his solar system research, Dr. Morrison has published more than a dozen books and is a coauthor on a popular introductory astronomy text, *Voyages Through the Universe*. He is the recipient of numerous awards, including the Klumpke-Roberts Award of the Astronomical Society of the Pacific for his contributions to science education.

Gopal Narayanan

Dr. Narayanan is a research assistant professor at the University of Massachusetts, Amherst. He received his bachelor's degree in electrical engineering from Anna University, Madras, India, in 1989, his master's degree in electrical engineering from Caltech in 1990, and his Ph.D. in Astronomy from the University of Arizona in 1997.

Millimeter and submillimeter wavelength molecular line observations provide the best opportunities to study the morphology, chemical composition, and dynamics of star-forming regions. Dr. Narayanan is involved in a three-pronged approach to a thorough understanding of the star formation process. On the instrumentation front, Dr. Narayanan is involved in the design and construction of advanced receivers and subsystems for millimeter and submillimeter radio astronomy telescopes. On the theoretical front, he performs radiative transfer modeling of the emergent spectra from star-forming regions, and on the observational front, he uses millimeter and submillimeter wavelength radio telescopes to perform observations to identify and subsequently understand the kinematics of regions containing embedded young stars.

Frazer N. Owen

Frazer Owen earned his B.A. from Duke University and his Ph.D. from the University of Texas at Austin in 1974. He is currently a tenured scientist at the National Radio Astronomy Observatory (NRAO).

Owen was involved in the initial organization of the Millimeter Array Project and served as Coordinator or Project Scientist between 1981 and 1998. The project, originally involving only NRAO, is now an international U.S.A/Europe/Japan project and is called the Atacama Large Millimeter Array (ALMA). Owen has served as a member of NASA and NSF oversight and review committees and several functioning on behalf of the National Optical Astronomy Observatory. He is a co-investigator for the SIRTF Wide-Area Infrared Extragalactic Survey (SWIRE) project on the upcoming Space Infrared Telescope Facility (SIRTF).

Owen's research interests include studies of radio emission from galaxies using the Very Large Array and related work with a variety of ground-based optical/infrared/millimeter telescopes, both public and private, as well as X-ray and optical space observatories. This work has concentrated on the effects of environment on active galactic nuclei and star formation activity in galaxies.

Judith Pipher

Judith Pipher earned her B.A. in 1962 from the University of Toronto and her Ph.D. from Cornell University in 1971. She served as director of the C.E.K. Mees Observatory (400 miles south of Rochester) from 1979 to 1994. Dr. Pipher is now a professor of astronomy at the University of Rochester.

Dr. Pipher's research is primarily in the infrared astronomy arrays and the development of infrared detector arrays. She and her collaborator William J. Forrest (University of Rochester) have undertaken the development of highly sensitive indium antimonide (InSb) arrays for the Space Infrared Telescope Facility (SIRTF) infrared array camera. She has also participated in the development of mercury cadmium telluride (HgCdTe) arrays. These arrays have been successfully used for observations of a wide variety of phenomena including the galactic center and planetary nebulae.

Tim Puckett

A pioneer in the field of amateur CCD astronomical imaging, Tim Puckett has built several robotic telescopes and is the discoverer of 42 supernovae to date (January 23, 2002). His spectacular comet photos have appeared on the pages of magazines worldwide.

Puckett's work has been featured in the popular media, and his images and articles have been been published in 17 countries. He is a coauthor of *The Art & Science of CCD Astronomy*. Puckett has been an active amateur astronomer for 21 years and an avid astrophotographer for most of that time.

Since 1989 he has owned and operated numerous CCD cameras. Currently, Puckett operates an automated Super Nova patrol and Comet Astrometry program with 60-cm and 35-cm robotic telescopes. He is a small business owner in Atlanta, Georgia, outside of which he operates the Puckett Observatory in the Appalachian Mountains. Puckett is also currently working as a robotic telescope consultant to many professional institutions

Mark Reid

Mark Jonathan Reid received his B.A. in physics from the University of California at San Diego in 1971 and his Ph.D. in planetary science and astronomy from Caltech in 1975. He is currently senior radio astronomer at the Smithsonian Astrophysical Observatory (SAO).

His research interests include black holes, active galactic nuclei, galactic structure, star formation, evolved stars, astrophysical masers, supermassive black holes, and Very Long Baseline Interferometry. His measurement of the proper motion of water masers at the galactic center significantly improved our estimate of the distance to the center of the Galaxy.

Vera Rubin

Vera Rubin received her B.A. in astronomy from Vassar College in 1948, and her Ph.D. from Georgetown University in 1954. She is currently an astronomer working at the Department of Terrestrial Magnetism at Carnegie Institution of Washington.

In the early 1970s, Dr. Rubin's observations of the rotation curves of galaxies indicated that there was more mass present (as indicated by its gravitational signature) than was observed in luminous stars. Her work was the origin of the "dark matter" problem, the fact that approximately 90 percent of the matter in the universe is of unknown composition. Her work laid the groundwork for many of the discoveries of galactic center black holes and halos of dark matter that are part of the current discussion of galactic structure and cosmology.

Anneila I. Sargent

Dr. Anneila I. Sargent is a professor of astronomy at the California Institute of Technology and director of Caltech's Owens Valley Radio

Observatory and of the Caltech/JPL Interferometry Science Center. She received her B.S. in physics from the University of Edinburgh (1964), and her M.S. and Ph.D. degrees in astronomy from the California Institute of Technology (1977). She was California Institute of Technology's 1988 "Woman of the Year" and was awarded the NASA Public Service Medal in 1998. In 2001, she was named an associate of the Royal Astronomical Society. From 1998 to 2001, she was a member of the National Research Council (NRC) Decadal Survey Committee on Astronomy and Astrophysics, and has served as president of the American Astronomical Society. She is also a member of the NRC panel convened to study the current management of astronomy in the United States, COMRAA (Committee on the Organization and Management of Astronomy and Astrophysics).

Dr. Sargent's research has concentrated largely on understanding how stars form in our own and other galaxies. Most recently she has been investigating the way in which other planetary systems are created and evolve. With her collaborators and postdoctoral scholars she uses the Owens Valley millimeter-wave array and the Keck telescopes to search for and study potential planetary systems from their earliest stages of formation when dense cores in interstellar clouds collapse to form stars to the epochs when individual planets may be born.

Debra Shepherd

Dr. Shepherd received her B.S. in physics in 1981 from the University of Cincinnati. She began her career as a research engineer and spent 10 years as an engineer, changing her focus to astronomy in 1988. During this time, as a contractor for NASA, she developed experiment simulators for Astro1, Astro2, and SL-J Spacelab missions at Marshall Space Flight Center. In 1991, she returned to graduate school and received a Ph.D. in astronomy at the University of Wisconsin in 1996. After graduation, she worked as a postdoctoral fellow at the California Institute of Technology, working with the Owens Valley Millimeter Observatory. In 1999 she joined the scientific staff at the National Radio Astronomy Observatory's Very Large Array in Socorro, New Mexico, where she now specializes in millimeter wave synthesis imaging and interferometric techniques.

Dr. Shepherd's primary research focuses on a multi-wavelength study of molecular outflows and accretion disks around massive young stellar objects (YSOs). Her thesis work clearly showed the prevalence of massive molecular outflows in regions of massive star formation.

She hopes now to gain a deeper understanding of the outflow powering mechanism. To accomplish this, she carries out observational projects using centimeter, millimeter, infrared, and visible wavelengths to define the characteristics of massive outflows and disks and to determine how these compare with low-mass YSO systems.

Carolyn Shoemaker

Carolyn Spellman Shoemaker is the leading comet discoverer of the 20th century. She has achieved worldwide recognition in her field as a planetary astronomer with the discovery of 800 asteroids and 32 comets—more than twice as many as any other woman in the history of astronomy.

After attending Chico High, she attended Chico State College, graduating *cum laude* with a degree in history. A year later, she received a master's and a teaching credential from Chico State.

Shoemaker has been a visiting scientist at the Branch of Astrogeology at the U.S. Geological Survey in Flagstaff, Arizona, since 1980. She received an honorary doctorate of science from Northern Arizona University, where she is now a research professor of astronomy. She is also a staff member at Lowell Observatory. She developed photographic techniques for use with the Palomar Schmidt telescope that greatly facilitate the detection of the fast-moving asteroids.

Her most significant discovery (with husband Eugene, and David Levy) was of the Comet Shoemaker Levy 9, which collided with Jupiter in 1994.

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H. Paul Shuch

H. Paul Shuch, who serves as executive director of the nonprofit SETI League, is a retired engineering professor credited with designing the first commercial home satellite TV receiver. A Vietnam-era Air Force veteran, Shuch pursued his education under the GI Bill, ultimately earning his Ph.D. in engineering from the University of California, Berkeley. He taught at several community colleges and the California State University before concluding his teaching career at Penn State's College of Technology.

A Fellow of the British Interplanetary Society, Paul is the author of nearly 300 publications, has received numerous honors and awards, and is a lifelong amateur radio operator well known for his microwave circuit designs. Paul served as director, technical director and chairman of the Board of Project Oscar Inc., builders of the world's first non-government communications satellites. He lives on a radio-quiet hilltop in northern Pennsylvania with his biologist wife.

Rashid Sunyaev

Dr. Rashid Sunyaev was educated at the Moscow Institute of Physics and Technology and Moscow University. He has been chief scientist of the Academy's Space Research Institute since 1992 and the chairman of the High Energy Astrophysics Department of the Russian Academy of Sciences since 1982. He is currently a director of the Max Planck Institute for Astrophysics in Garching, Germany, and editor in chief of *Astronomy Letters and Astrophysics and Space Physics Reviews.*

Dr. Sunyaev's contributions have been both deep and broad. He and Yakov B. Zel'dovich proposed what is known as the Sunyaev-Zel'dovich effect, a valuable method used to determine absolute distances in the universe. In other work, Dr. Sunyaev and N. Shakura proposed a model of accretion through disks onto black holes. His research has also included important studies of the early universe, including the formation of the cosmic microwave background (CMB) radiation discussed in Chapter 1.

Jill Cornell Tarter

Dr. Tarter received her undergraduate degree in engineering physics from Cornell University and her Ph.D. in Astronomy from the University of California at Berkeley in 1975, where her major field of study was theoretical high-energy astrophysics. As a graduate student at Berkeley, she became involved in a small search for radio signals (Project SERENDIP) from extraterrestrial civilizations using the Hat Creek Observatory 85-foot telescope.

As a principal investigator for the nonprofit SETI Institute in Mountain View, California, Dr. Tarter served as project scientist for NASA's High Resolution Microwave Survey (HRMS) until its termination by Congress in October 1993. On September 15, 1997, the board of directors of the SETI Institute appointed Dr. Tarter to a new endowed position: the Bernard M. Oliver Chair for SETI. Dr. Tarter is currently director for SETI at the SETI Institute.

Joseph H. Taylor, Jr.

Joseph Taylor received his undergraduate degree in Physics from Haverford College, and his Ph.D. from Harvard University. He was on the faculty of the University of Massachusetts at Amherst, and currently a professor of Physics at Princeton University.

One of only two astronomical researchers to earn the Nobel Prize in Physics during the last decade, Dr. Taylor remembers building a working radio telescope for a senior project at Haverford College. The Nobel Prize in 1993 was awarded for the 1974 discovery (using the 300-meter-diameter Arecibo Radio Telescope in Puerto Rico) of the first pulsar in a binary system. Such pulsars are perfect test environments for Einstein's general relativity theory. The co-recipient of the Nobel Prize in 1993 was Russell A. Hulse, his research student at the time. Dr. Hulse is also a physicist at Princeton University.

Meg Urry

Meg Urry received her B.A. from Tufts University in 1977 in physics & mathematics *summa cum laude*, and her Ph.D. from Johns Hopkins University in 1984. She worked as an astronomer at the Space Telescope Science Institute (STScI) from 1987 until 2001, and recently was named professor of physics and director of the Yale Center for Astronomy and Astrophysics at Yale University

Dr. Urry's research is centered on objects called *active galaxies*, which are galaxies with unusually luminous centers (cores). Many theories propose that the source of the luminosity is a massive black hole. Her research (using ground- and space-based telescopes sensitive across the electromagnetic spectrum) seeks to explain some of the most energetic phenomena in the universe.

She is chair of the Commitee on the Status of Women in Astronomy of the AAS and has long been interested in the issue of women in science. She was the organizer of the 1992 Women in Astronomy conference that led to the Baltimore Charter (see Chapter 4).

Sylvain Veilleux

Dr. Veilleux was born in Montreal, Canada, and earned his bachelor's degree in physics from the University of Montreal in 1984. He spent five years at the University of California, Santa Cruz, where he obtained his master and doctorate degrees in astrophysics in 1986 and 1989, respectively. His Ph.D. thesis consisted of a detailed "Study of the Structure and Dynamics of the Narrow-Line Regions in Seyfert

Galaxies." Veilleux subsequently worked at the University of Hawaii, supported in part by an NSERC postdoctoral fellowship, and in 1992, was awarded a Hubble Fellowship. He used the Hubble Fellowship to work at the headquarters of the Kitt Peak National Observatory (KPNO) in Tucson, Arizona. Since 1995, Veilleux has been a faculty member at the University of Maryland, College Park.

His research interests center on understanding the nature, origin, and impact of starburst/black hole–driven activity in galaxies, and on the formation and evolution of galaxies. Most of his work involves the analysis of ground-based observations at optical and infrared wavelengths supplemented with data obtained with astronomical satellites.

Ashley Zauderer

Ashley Zauderer is a senior at Agnes Scott College, a women's college in Atlanta, Georgia. Zauderer attended high school in the suburbs north of Atlanta and arrived at Agnes Scott College in 1998. She spent three months in 2000 as a summer Research Experience for Undergraduates (REU) intern at the Very Large Array in Socorro, New Mexico.

Her summer project with W. Miller Goss was an investigation of small-scale structures in galactic neutral hydrogen (HI). She used data from the Very Long Baseline Array to map the absorption of HI against a number of bright sources, including 3C138. In addition to this project, the summer students made observations of a brown dwarf and by chance detected a flare in radio brightness of the source. The results were published in *Nature* in the spring of 2001 (Vol. 410, p. 338), and the source continues to be monitored.

Ellen Zweibel

Dr. Zweibel received her B.A. from the University of Chicago (1973) and her Ph.D. from Princeton University (1977). Since 1980, she has been on the faculty of the University of Colorado. In addition, she is an Affiliated Faculty Member in the Department of Applied Mathematics.

Dr. Zweibel's research concerns the origin and evolution of astrophysical magnetic fields. Such fields are known to exist in stars, galaxies, and the intergalactic medium. She studies these fields and the ways in which they influence their environments, most recently focusing on magnetic fields in the convection zone of the sun and in interstellar molecular clouds.

Chapter Six

Unsolved Problems, Unanswered Questions

As this book is being written, there are an enormous number of unsolved problems and unanswered questions in a variety of scientific fields. Biologists and chemists ponder the origin of self-replicating organisms. Neuroscientists explore the nature of thought and memory. And astronomers add a large number of unsolved, fundamental problems to the list of topics that humans are seeking to understand. One of the constants of human exploration is that we often do not find what we are looking for, but something entirely new. Although we define the questions, nature ultimately defines the answers, and these answers often take us in new and unexpected directions.

In this chapter, we seek to enumerate some of the most important unanswered questions in astronomy and astrophysics. Naturally, the topics in this chapter, because they are both fundamental and unanswered, are the subject of some of the most intense attention of specialists in the field. Some questions that, up until very recently, were considered unanswered have now been answered. For example, scientists in early 2001 provided an explanation for an issue that had been dubbed "the solar neutrino problem." The detection of extrasolar planetary systems, discussed in detail elsewhere in the book, is only about five years old, and the existence of such planets has answered some of the questions about the uniqueness of our situation here on Earth. The discovery that the universe is not only expanding but accelerating in its expansion is likewise only a few years old. And recent observations using the effect of gravitational lensing have given us some of our first views of the "building blocks" of galaxies, collections of young stars that are only a few hundred million years old. These stars represent protogalaxies that eventually formed into the spiral, elliptical, and irregular galaxies we see today.

Any list of unanswered questions is only a snapshot in time, and given the accelerating rate of discovery, these snapshots are outdated rapidly. In this chapter, we have tried to focus on questions not only that are currently unanswered but that are likely to remain unanswered for some time. Our list starts with questions about the solar system we inhabit and other planetary systems, moves out to the stars, into the realm of galaxies, and finally out to the farthest reaches of space that we can probe. Some of the questions on this list will have to be addressed by interdisciplinary teams of scientists, a trend that has been accelerating in recent years. We list the questions briefly below, then turn to each of them in more detail.

1. *Is our solar system typical or atypical?* Even with the rapid current rate of discovery, it will take decades to assemble a list of planetary systems large enough to analyze statistically, and only then—with the addition of the first space-based infrared interferometers—will we be able to assess how rare or common our solar system is. We still do not know how common are planetary systems with terrestrial planets in nearly circular orbits within the host star's "habitable zone."
2. *Is life common in the universe, rare, or unique to the Earth?* A variety of factors may govern the origin and survivability of life in the universe. Until we detect life (even simple life) somewhere other than here on Earth, we will not begin to know how common life is. Both direct and indirect methods to detect life on other planets are at least a decade away.
3. *What is the origin of global warming? Can we do anything about it?* This question is clearly an interdisciplinary one. While we have known about the existence of global warming for quite some time, the cause is still vigorously debated, and unlike many questions tackled by astronomers, this one has major political and economic overtones that muddy the waters of debate.
4. *Can potentially dangerous asteroids be tracked and perhaps eliminated?* Several observational programs (described in this book) are now under way to determine the trajectories of near-Earth asteroids. If we are unable to come up with methods to divert

such object that are on a collision course, we may be eliminated as a species.

5. *Is there a black hole at the galactic center and at the center of all galaxies?* Evidence is very strong that there is a black hole at the center of the Milky Way galaxy. Do all galaxies have black holes lurking in their nuclei? Would the ubiquitous presence of black holes in galactic centers tell us something about their formation?
6. *How did the first galaxies form?* While astronomers have a fairly complete picture of the evolution of galaxies in the current universe, there is still significant debate about the way in which the first luminous objects coalesced. What were the "seeds" or "kernels" for the formation of the first galaxies?
7. *What are dark matter and dark energy? Dark matter* is the general term used to describe any material that has a gravitational effect on luminous matter but unknown physical composition. Astronomers and physicists are still trying to determine what type of material might compose the more than 90 percent of the matter in the universe that is "dark." Recent discoveries indicate that dark energy may also be present and may be causing the universe to expand at an accelerating rate.
8. *What is the origin of the fluctuations seen in the early universe as evidenced by small fluctuations in the cosmic microwave background?* Recent studies have definitively proven the existence of fluctuations in the CMB. What is the origin of these fluctuations? Do these fluctuations give us insight into the earliest times in the universe?
9. *Have physical constants changed with time? If so, what is the meaning of this variation?* There are proposals that the physical constants that define the universe (e.g., the fine structure constant, have changed with time. Studies of the light from very distant objects (quasars) have the potential to reveal the evolution of these constants with time.
10. *Is there a Theory of Everything (TOE)?* The two most successful theories in physics (general relativity and quantum mechanics) have yet to be unified in a single all-encompassing theory. There are promising signs from an area of research called *string theory*, which posits that all particles and forces are lower-dimensional manifestations of higher-dimensional vibrations. A unifying theory that would encompass both general relativity and quantum mechanics is called a Theory of Everything.

PLANETARY SYSTEMS

Our Solar System

Recent observations have started to identify and characterize planets orbiting a large number of nearby stars. As astronomers had long suspected and proposed, solar systems appear to form naturally as byproducts of star formation. Just as no baker can incorporate all the flour into the cake, so some material lingers after the gravitational collapse that forms a star. This remaining material, though, may take a variety of configurations. The planetary systems that we have found thus far make it clear that systems like our own—with small terrestrial planets and large Jovian (gas) planets orbiting in nearly circular orbits—are not the only possible end product. In fact, the majority of systems that have been discovered thus far look very little like our own solar system.

One reason for the apparent dearth of "solar-type" planetary systems is the currently available method of searching for planets. The Doppler method (described in Chapter 1) detects the back-and-forth "wobble" of a star that is orbited by planets. This type of wobble is most easily detectible for large planets in small orbits. Not surprisingly, the first detections with this method have been large planets in small, highly elliptical orbits.

However, the uniqueness of our planetary system is very much an open issue. We simply have not discovered enough planetary systems with large planets in large orbits to compare them with our solar system. If one considers that some 70 planets have been discovered in the last 5 years, even assuming a constant rate of discovery (though the rate is certainly accelerating), we would expect to know of more than 200 planets by the year 2010. The number of known systems in 10 years is likely to be far higher.

Why is the uniqueness of our solar system a vital issue? In some sense, because one of the other great mysteries—Are we alone in the universe?—depends on the answer to this question. If hospitable environments for life as it exists here on Earth are common in the universe, then we might expect that there are other inhabited worlds out there. If the particulars of the solar system are unique, or even rare, it might put a damper on our hopes to find other life in the universe. In addition to the quest to discover other life, the answer to this question will tell us much about how planetary systems form.

Life in the Universe

One profound mystery, and one that is likely to remain so for quite some time, is whether we are alone in the universe as living organisms and as intelligent beings. If we find (in our quest to answer the first question discussed above) that there are a large number of habitable systems in our neighborhood of the Milky Way, then we may have greater hope for success in our search for life in the universe.

The search for life in the universe has two main thrusts: (1) the search for biological evidence for life in environments other than the Earth and (2) the search for the potential communications that other civilizations might broadcast. Both searches confront monumental technical and scientific challenges, but one battle, the quest for the respectability of the search itself, seems to have been won. There are few people who question the validity of the search, and as astronomers working in many diverse areas turn up more and more evidence for the widespread presence of complex molecules in the harsh environment of interstellar space, it is starting to seem more likely that we will eventually discover other life.

The last targeted missions to look for life elsewhere in the solar system were the Viking I and II missions to Mars. In particular, the Viking landers were equipped with self-contained biology experiments that used soil samples to test for the presence of life. While there was some initial excitement over positive reactions that indicated the presence of living simple organisms, NASA eventually concluded that the reactions were false positives and that the results told us more about the very different chemistry possible on the harsh Martian surface than about the presence of any biological activity.

More recently, an Antarctic meteorite made headlines with the possibility that it contained the fossilized remains of a simple organism that lived on Mars early in the history of the solar system. The claim was immediately questioned, and the debate still rages over whether the meteorite contains clear evidence of previous life. This discovery and other searches for the presence of simple life forms, or their fossilized remains, have shown scientists how difficult it can be to design experiments that unambiguously show evidence for the presence of life. Some have suggested that until geologists hit the ground on the surface of Mars and examine regions of the surface in detail, we will not have unambiguous evidence. And once humans are on the surface of Mars, there is the distinct possibility that our presence will introduce Earth-borne bacteria. If we find bacteria on Mars that look like Earth-based organisms, will we have found a link between the origin of life on the two planets or simply our own contamination?

The other potential location for life in the solar system that is often mentioned is Jupiter's moon Europa. That moon appears to be an ice-enshrouded ocean, and the gravitational stresses on the moon caused by the massive parent planet seem to keep the subsurface ocean liquid, despite the low ambient temperatures in this outer part of the solar system. There are plans on NASA drawing boards for a Europa probe that would explore the subsurface oceans for signs of life. However, all of the missions mentioned are a decade or more in the future and face uncertain funding. The question of whether there are other simple biological organisms even in our own solar system is likely to be unanswered for a decade or more.

The second tactic in the search for life in the universe is to use large radio telescopes to scan for signals of extraterrestrial origin. This search was made famous in the movie *Contact*, based on Carl Sagan's book of the same name. The Search for Extraterrestrial Intelligence is discussed in Chapter 3 in more detail. The SETI effort is highly sophisticated and uses cutting-edge electronics and scanning technologies. SETI received a large financial boost in August 2000 when two philanthropists (Paul G. Allen and Nathan Myhrvold) pledged $12.5 million to the project. The project that had previously depended on time purchased on other telescopes will now have an instrument dedicated to the search. If this search is eventually to meet with success, the recent funding has moved that date closer.

Global Warming

The issue of global warming is not the sole purview of astronomers, of course, but astronomy and astrophysics—in particular, studies of other planetary bodies in the solar system—might tell us a great deal about the eventual fate of our planet's atmosphere and whether we as humans can do anything about it. Atmospheric scientists, geologists, physicists, chemists, biologists, and others all contribute to the debate over whether the Earth's mean temperature is on the rise and, if so, the contributing factors to that rise. The history of the Earth is approximately 4.5 billion years long, and changes over the last several hundred thousand years, while significant to humans, may not be significant to the evolution of our planet as a whole. There is also significant disagreement over whether carbon dioxide (one of several so-called greenhouse gases) is to blame for the recent rise in the Earth's temperature.

Before any attempts are made to remedy the problem of Earth's rising temperatures, scientists need to come to an agreement about the severity of the rise and its cause. While some in the scientific community have come to a consensus that the increased output of carbon dioxide resulting from human activity is to blame, others are not convinced. James Hansen summarized the debate succinctly in a 1999 online article (referenced below). One important point that he raises is that another decade of data is required before scientists will be able to successfully compare models for temperature change with actual temperature fluctuations. He clearly sets out the fundamental differences between the two "camps"—those who see evidence for global warming and those who do not.

It is important to remember in the global warming debate that life on our planet requires that there be some greenhouse effect. Our atmosphere of water vapor, carbon dioxide, and other gases raises the surface temperature above the freezing point of water, which has proven vital to life on this planet. The debate that rages is over what has been called the "anthropogenic" greenhouse effect. Hansen notes that science progresses most effectively when all parties involved are willing to challenge assumptions and theories with new, reproducible experiments. The fact that the experiment involved is the Earth's atmosphere and our impact upon it means that this debate will certainly rage well into the twenty-first century.

Dangerous Asteroids

Potentially hazardous asteroids are a difficult problem for policy makers and politicians, who have to decide whether or not to fund particular projects. The probability of a major asteroid or comet impact with the Earth is exceedingly small. However, the effects of such an impact could be disastrous, with the largest such events being dubbed "planet killers." Geological records remind us that the Earth is not immune to such impacts but also reassures us that they occur very infrequently.

As is described in Chapter 3, there are several projects that are dedicated to the search for potentially hazardous near-Earth objects (NEOs), and the goal for these projects is to determine their sizes and trajectories. The Near Earth Asteroid Tracking project is a NASA-funded effort that has had considerable success in identifying and tracking near-Earth asteroids. The NEAT Web site is constantly updated with newly identified objects (http: neat.vpl.nasa.gov/).

The NEAT project has a detection threshold of approximately 100 m, and objects up to 500 m in diameter could cause considerable damage on the surface of the Earth, though the damage would likely be localized. Objects of this size are thought to impact every 1,000 to

10,000 years. Objects that are 500 m to 1 km in diameter are both more rare and more dangerous. They are believed to impact every 100,000 years or so. Comets of the same size are even more rare, with impacts every 500,000 years.

The NEAT program has a 10-year goal of identifying the majority of near-Earth asteroids that are 1 km in diameter or larger. Soon after the project began, the estimated number of such objects was reduced from the 1,000–2,000 range to the 500–1,000 range. NEAT scientists expect that there is a 1-in-1,000 chance of discovering an asteroid likely to hit the Earth in the next 100 years and a 1-in-10,000 chance of finding one that would hit the Earth in the next 10 years. Chances of finding an asteroid that would hit within a year are diminishingly small, 1 in 100,000. In the event that such an asteroid were discovered (Hollywood scenarios notwithstanding), there would be little that we could do as a planet. Despite the potential for devastating effect, the programs that search the skies are funded at a fairly modest level, below $1 million in total per year. By 2010, we should know whether the Earth faces a near-term threat from such an object.

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GALAXIES AND BLACK HOLES

The Galactic Center

Stars congregate into galaxies, and our host galaxy is called the Milky Way. Astronomers' studies of other galaxies have shown us that each galaxy consists of several hundred billion stars and that the evolution of these constituent stars can have a profound impact on the evolution of the galaxy; stars are to galaxies what cells are to our bodies. Astronomical observations and theory have given us a thorough understanding of the evolution of stars, while our understanding of the evolution of galaxies has lagged. The early history of galaxies is lost in the distant reaches of a difficult-to-observe early universe. Telescopes described in Chapter 2 will open some new windows; in particular, the Next Generation Space Telescope will be optimized to observe in the infrared part of the spectrum and thereby give us unprecedented views of highly redshifted (that is, young) galaxies in formation.

While astronomers are interested in characterizing and understand the general properties of galaxies, the distance between galaxies often makes it difficult to examine other galaxies in detail. On the other hand, our placement in the disk of our own galaxy makes it difficult to study the nearest of all galaxies, our own. In particular, the dust and gas in the plane of the Milky Way have made it difficult to observe the center of our own galaxy.

However, the coming decades are likely to increase our knowledge of the galactic center region greatly and in particular to answer the question of whether the Milky Way, and all galactic nuclei for that matter, are host to black holes. As we begin to understand better the modes in which galaxies and clusters of galaxies formed, we will be able to determine whether black holes at galactic centers are in some sense inevitable, in the same way that fusion at the center of a star of sufficient mass is inevitable.

There is a variety of evidence that the center of the Milky Way galaxy does host a black hole. All of the evidence discovered thus far is circumstantial: the rapid rotation of stars near the galactic center, the presence of large magnetic fields seen in radio frequency observations, the recent discovery of X-ray flares by the Chandra X-ray observatory, which may indicate material in the accretion disk of a black hole. But what are the prospects for a clear detection of the signature of a black hole? When might we expect to see an “image” of a black hole? Or is that even a valid expectation?

It turns out that high-frequency observations made with radio interferometers (see Chapter 2) are resolving a smaller and smaller region known as Sagittarius A*, the dynamical center of the Milky Way. Astronomers are observing regions that are only a factor of a few times larger than the Schwarzschild radius that is expected to be associated with a galactic center black hole. Current radio frequency observations are resolving objects that are only 100 million kilometers across: no mean feat at the distance of the center of our galaxy. And the black hole at the galactic center is expected to have a Schwartschild radius of about half that amount. As astronomers push interferometric observations into the submillimeter regime, they expect to be able to detect the “shadow” of a black hole at the galactic center. Computer modeling of the behavior of light in the environment of a black hole of a given mass could be compared with the observed emission at high frequencies to determine whether there is an unambiguous detection of a black hole at the galactic center. The technology of millimeter wave Very Long Baseline Interferometry (VLBI, see Chapter 2) will be vital to make these observations.

How Did the First Galaxies Form?

When astronomers look back to the formation of galaxies, the disciplines of extragalactic astronomy and cosmology begin to blur. This occurs because evidence is growing that the primordial fluctuations in density suggested by the fluctuations now detected in the CMB (see below) may be related to the formation of the largest-known structures. Astronomers have made large-scale maps of the universe, plotting the positions of galaxies, and they have found that galaxies are not uniformly distributed throughout space but congregate into collections of galaxies called clusters and superclusters.

The question remains, though, did stars form first, then gravitationally collapse to form galaxies, or did the material that comprises a galaxy collapse around some "seed" mass (perhaps dark matter) and then form stars later? This debate is sometimes described as the "bottom-up versus top-down debate." Did the universe initially collapse into enormous sheets of material that we now see as the spongelike distribution of clusters of galaxies, or did these large-scale structures arise slowly as the universe aged?

Why has our knowledge of galaxy evolution lagged so far behind, say, our knowledge of the evolution of stars, which is quite thorough? It has something to do with our ability to see "young" galaxies versus our ability to see young stars. As we look out into our own galaxy, the Milky Way, we can observe the full panorama of the life cycle of stars, from the stellar nurseries in Sagittarius and Orion to the death explosions of supernovae and planetary nebulae. Since we can observe all of these stages (which differ for stars of differing mass), we are able to construct scenarios as to how stars evolve.

But galaxies are so distant that most of the galaxies that we can see are not much younger than our own. The deeper we look into space (with more sensitive telescopes, see Chapter 2), the more distant, and therefore younger, objects we are seeing. To see galaxies in formation, we need to observe the universe as it existed in its first few million years. The capabilities of the Space Infrared Telescope Facility and the

Next Generation Space Telescope will move astronomers closer to answering this important question.

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COSMOLOGY

What Are Dark Matter and Dark Energy?

Astronomers have come to the stunning conclusion that we don’t know what most of the universe is made of. These unknown components of the matter and energy in the universe are referred to as dark matter and dark energy. Dark matter has been hypothesized since the rotation curves of galaxies suggested to Vera Rubin in the 1960s that there was more mass in galaxies than was apparent in their stars and gas. In a now-famous result, Rubin proposed that there was some as-yet-unknown form of matter that caused rotation curves in galaxies to level out at large radii in galaxies rather than “turn over,” as one would expect if the material in a galaxy were in Keplerian rotation.

The motions of planets in the solar system are examples of Keplerian rotation. Planets farther out orbit the sun more slowly, following Kepler’s laws. However, astronomers like Rubin, who first measured how fast material far out in a galaxy was rotating about its galactic center, were surprised to find that the velocities rose out to large radii and eventually “flattened out,” meaning that beyond a certain radius, the material was moving at a constant velocity (Figure 6.1). This result suggested that there was some material that was present in larger amounts far out in a galaxy that kept the stars and gas out there moving at high velocities.

The importance of this discovery was not immediately recognized, but in the ensuing decades, more and more observational evidence was discovered implying that the universe contained some sort of matter that did not emit radiation—thus “dark matter.” The motion of stars in galaxies was the first evidence. The motion of neutral hydrogen

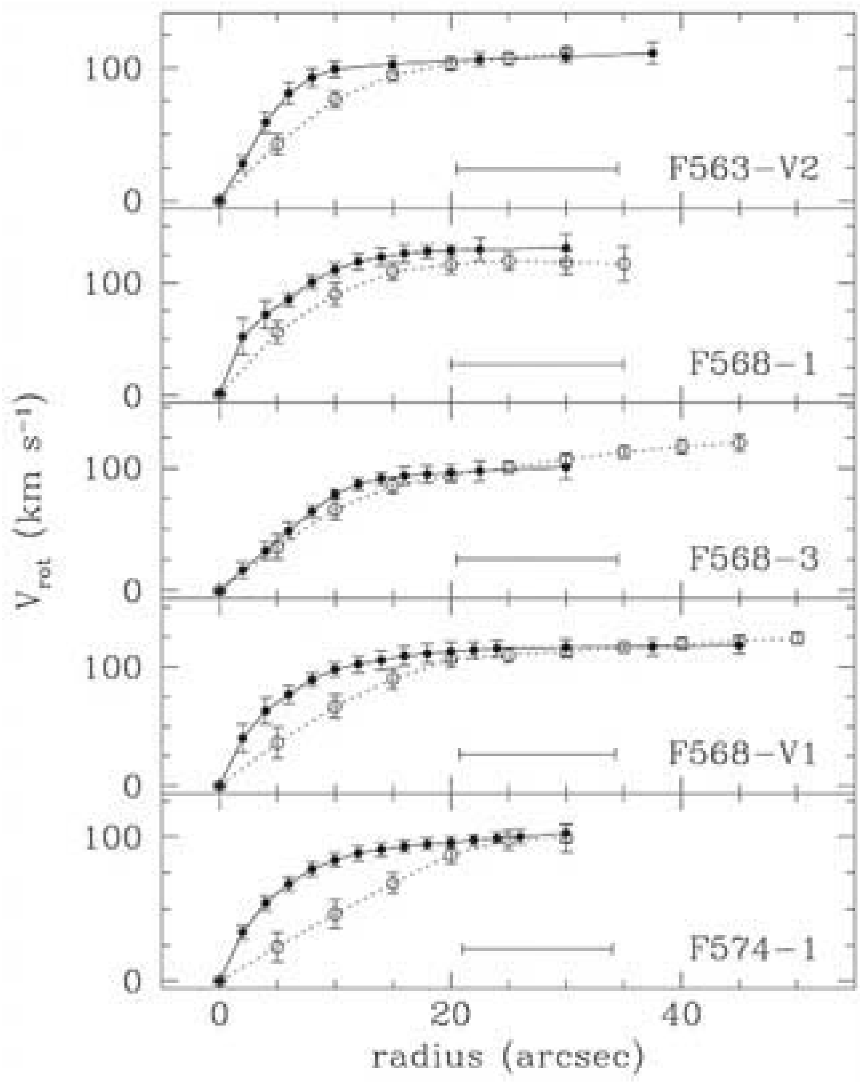

Figure 6.1. The rotation curves of five low-surface-brightness galaxies. The *filled circles* are data from ionized hydrogen, and the *open circles* are previously published data from neutral hydrogen (HI). Note that the rotation curve is "flat" out to very large radii. From R. A. Swaters, B. F. Madore, and M. Trewhella, "High Resolution Rotation Curves of Low Surface Brightness Galaxies" *Astrophysical Journal Letters*, 531 (2000): L107. Used with permission.

(HI) in galaxies revealed a similar trend, and on even larger scales, it was discovered that the motions of galaxies in clusters implied the presence of (fractionally) an even larger percentage of dark matter than was found on the scales of galaxies. Whatever this dark matter was, it appeared to be insignificant on small scales (like stars and solar systems) and dominant on large scales (like galaxies and galaxy clusters). Once astronomers agreed that dark matter existed, the debate and investigation began in an effort to determine what it might be. What was the nature of this undetermined part of the universe? In the Milky Way, dark matter appears to constitute 90 percent of the mass. On larger scales (for example, in rich clusters), dark matter appears to constitute upwards of 99 percent of the mass.

We only know about dark matter because of its gravitational effects on luminous matter, things like stars and gas, which we can detect with traditional telescopes. However, it is important to emphasize that the abundance of dark matter is also apparent in some of the fascinating effects associated with general relativity. For example, Einstein postulated that in the presence of mass, space itself distorts, so that light passing through that region of space bends. This prediction was first tested during Einstein's lifetime with the apparent displacement of the position of a star near the limb of the sun during a solar eclipse. A more dramatic effect is seen in the so-called Einstein rings (Figure 6.2) and crosses that have been discovered in deep images of the universe. These are distant sources (often quasars), the light from which is distorted by the presence of a massive foreground object. Like light passing through a lens, the background source is "lensed" by the mass of the foreground galaxy, producing a distorted image of the background source. The mass implied by the distorted image shows that the foreground lensing objects are dominated by dark matter.

What might this dark matter be? That is one of the great, unanswered questions in astronomy, and there are certainly candidates. It might be made of normal particles (like the protons, neutrons, and electrons that make up the atoms in our bodies) or some exotic particles not yet discovered. If the dark matter is contained in normal particles, then it must be nonluminous or of so low luminosity that it would be difficult or impossible to detect.

Black holes, brown dwarfs, and white dwarfs are some of the "normal" objects that might make up at least a portion of dark matter. Black holes in particular emit no radiation, and brown dwarfs emit radiation at very low levels. Such objects that might be located in the halo of our own galaxy have been dubbed MACHOs (Massive

Figure 6.2. Einstein rings are the result of a nearby object gravitationally distorting the light from a much more distant object. These images show two such rings: One (*left*, MG1131 + 0456) was detected with the Very Large Array in 1987 and was the first ever discovered, and the other (*right*, B1938 + 666) was discovered with the Multi-Element Radio-Linked Interferometer Network (MERLIN) radio telescope array. The image of B1938 + 666 shown here is a follow-up observation made with the Hubble Space Telescope. Courtesy of the National Radio Astronomy Observatory and the Space Telescope Science Institute.

Compact Halo Objects), and searches are under way to detect them. However, such objects can only account for at most 50 percent of all dark matter. The rest of dark matter must be something fundamentally different. There is a word that refers generically to another dark matter candidate, called a WIMP, or Weakly Interacting Massive Particle. These particles might be detectible in particle accelerators, but, like neutrinos, they are by their nature difficult to detect. To detect neutrinos, elaborate experiments, involving tons of fluid and subterranean chambers, have been conducted. The detection of WIMPs is going to be challenging, and if such particles do exist, it may be decades before we know more about them.

"Dark energy" is the partner term to "dark matter," which is an attempt to explain a more recent observation. The work of Saul Perlmutter and Alex Filippenko (see Chapter 1), who have used distant Type Ia supernovae as standard candles, indicate that the universe is not only expanding but also accelerating in its expansion. That is, distant supernovae are brighter than one would predict in a universe expanding at a constant rate because, in the past, the universe was expanding more slowly.

Gravity pulls massive objects together, so astronomers and physicists have begun the quest to determine what energy might be present to push things apart on large scales, an effect that looks like the opposite of gravity. Since this effect requires energy, and since astronomers do not yet know the nature or the source of the energy that is doing the pushing, they have dubbed it dark energy. Perlmutter gives credit to cosmologist Michael Turner for the term.

Albert Einstein first suggested the presence of a repulsive force in 1917, when he needed a way to keep the universe in a steady state, supported against gravitational collapse by a term called the *cosmological constant*. The term was discarded once Edwin Hubble showed that the universe was expanding, but it appears that a similar term is needed yet again, albeit for a very different reason. One leading proposal is that the dark energy is contained in the vacuum of space. This is not as outlandish as it sounds, since physicists have discussed for decades that the vacuum of space is a source of virtual particles that appear and annihilate constantly. However, this idea runs into serious problems in execution, since it seems that such a well of energy would not allow the universe to hang together as it apparently has. A second idea, dubbed *quintessence*, is that there is a field threaded through the universe, like the gravitational field, that has a repulsive effect, accelerating the expansion of the universe over time.

The search for dark energy is in its infancy, and many astronomers and physicists feel that the accelerating expansion of the universe might be an observational clue that the universe is a very different place than we have been able to describe thus far. With most of its mass and energy "dark," the luminous universe that we generally have described in this book seems to be only the foam on an enormous unknown sea.

What Is the Origin of Fluctuations in the Cosmic Microwave Background?

This question relates to several other unanswered questions that astronomers have asked, in particular, concerning the origin and formation of galaxies in the early universe. If one imagines that the early universe was perfectly homogeneous, then it is difficult to understand how it could ever have evolved into such a clearly unhomogeneous place, at least in terms of luminous matter. Interstellar space is almost a perfect vacuum, and the cores of stars (especially stellar corpses like neutron stars and black holes) are the densest environments imaginable. How could such an unhomogeneous universe arise from a perfectly smooth primordial fireball?

Fortunately for the fate of this universe, the distribution of mass and energy was not entirely smooth but appears to have had small fluctuations in density, which astronomers have recently detected by looking carefully at the remnant of the Big Bang that is called the CMB. In Chapter 1, we have described the BOOMERANG results, which indicate that fluctuations exist and that they have a scale size that supports the idea of a flat universe. It is now clear that there had to be minute density variations in the "photon-baryon fluid" that was the early universe. The question remains, however: How did these fluctuations arise, and what might the presence of these fluctuations tell us about the interactions between mass and energy in the first 300,000 years of the universe?

Have Physical Constants Changed with Time?

Scientists have generally assumed that the universe is everywhere and at all times the same, in terms of its basic physical laws. This assumption is necessary if astronomers are to extrapolate our knowledge gained from local studies to studies of the universe as a whole. If astronomers derive a value for the gravitational constant through Earth-based experiments, for example, they have generally assumed that the same constant is valid in a far-flung portion of the universe. However, as early at 1937, physicist Paul Dirac suggested that physical constants might change with time.

Recent experiments by a group of astronomers based in Australia have cast doubt on the assumption of unchanging physical constants. The results, if confirmed, might have far-reaching effects. (A paper by John K. Webb of the University of New South Wales and collaborators was published in *Physical Review Letters* in the summer of 2001.) The Australian group's research has detected a small but measurable change in the value of the fine structure constant, a value that defines the strength of the electromagnetic force. Studying the absorption from distant clouds of gas (some so distant that they represent the universe when it was only 10 percent of its current age), Webb and collaborators found that the value of the fine structure constant has changed over time, and the size of the constant appears to be proportional to z (the redshift). Since the fine structure constant is dependent on the speed of light, one possibility is that changes in the speed of light from the time of the early universe until now could account for the change in the value of the fine structure constant.

If this early result is confirmed in other independent observations, it might help the case for string theory. String theorists propose that the four-dimensional world of space and time that we inhabit is a subset of what is truly a 10-dimensional universe and that the fundamental particles and forces are different vibrations on these higher-dimensional "strings." Among other benefits (see below), string theory might be able to account for changes in the fine structure constant—if the result is verified.

Is There a Theory of Everything?

"Unifications" have been a persistent goal of physicists since the time of Isaac Newton. He first proposed that the same force (gravity) governed the motions of objects on Earth and in the heavens. James Clerk Maxwell in the nineteenth century developed a formalism to unify optics with the electric and magnetic forces in his electromagnetic theory. What is now called the *Standard Model* can successfully describe all of the known subatomic particles and interactions and has unified the electromagnetic and weak nuclear forces (the so-called electro weak interactions). Physicists have since been trying to develop what is called a grand unified theory (GUT), which would unify the ways in which the electro weak and strong nuclear forces (which apply to particles like protons and neutrons and their building blocks, quarks) are described. Even a successful GUT, however, would leave out another important force, namely, gravity, which is currently described theoretically by Einstein's general relativity, developed in the early part of the twentieth century.

One of the striking aspects about all of these independent forces is that they have vastly different strengths as measured in the current universe. Particle physicists have noted, though, that the relative strengths of the forces depend upon the energies at which they are measured. At low energies (like those in the current universe), the gravitational force is nearly 10^{40} times weaker than the electric force. However, at sufficiently high temperatures and energies—like those that must have existed early in the history of the universe—the relative strengths of the forces all become equal. This observation suggests that at high enough energies, all of the separate forces that we now observe could be described with a single formalism.

Therefore, physicists and astronomers currently have theories that separately and successfully describe the very small and the very large in the universe and make testable predictions. The Standard Model is what is known as a quantum field theory. Quantum mechanics is the theoretical framework that describes the subatomic world, and Einstein's general relativity encompasses Newton's earlier description of gravity and makes additional predictions that have been borne out in observation. However, the structure of quantum mechanics and general relativity are very different, and the ultimate goal is a single theory that would unite these two descriptions. Such a new theory would have to agree with the predictions of quantum mechanics *and* general relativity but describe both within a single theoretical framework. Einstein worked on this problem unsuccessfully for nearly 30 years. This theory has sometimes been called a Theory of Everything, and it now appears that a TOE would also have to describe another force (quintessence) that accelerates the expansion of the universe. Cosmologists such as Steven Hawking and Steven Weinberg have predicted that it will be several decades or more before a Theory of Everything exists, with Weinberg saying that it may be 2050 or 2150 before a successful theory is developed, which can describe all known forces.

What is called superstring theory is one of the most promising paths of inquiry into a Theory of Everything. There are times and settings in the universe that require a combination of small scales and large masses: namely, the singularity of a black hole, and the early moments of the history of the universe. Clearly, the settings that require a TOE for thorough understanding are often astronomical in nature.

Superstring theory proposes that all forces and particles correspond to different resonances on strings or membranes within a universe containing 9 spatial dimensions and time, for a total of 10 dimensions. Six of the spatial dimensions are “curled up”, or hidden, so that we perceive the universe to have only 3 spatial dimensions. One of the major benefits of string theory is that it can be used to determine from first principles the masses and charges of fundamental particles. However, the theory is far from complete, and work continues in earnest.

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CONCLUSION

The quest for answers to the questions enumerated in this chapter is likely to raise a number of even more profound questions. The search that has led astronomers to this point in our understanding of the universe is likely to take us in new and unexpected directions for the foreseeable future.

Chapter Seven

Careers in Astronomy

As the light of day fades away, the astronomer slowly walks from his cabin to the nearby observatory dome atop a pine-covered mountain. After laboring up the stairs, he reaches out to turn on the dome lights illuminating a large telescope, the small control desk placed nearby, and the interior of the grand dome of the observatory roof. Pressing a button on the wall, he opens the dome to prepare the telescope for a night of observing. The dim glow of twilight remains outside in the sky, but the brightest stars are surfacing into view through the fading twilight. Casually paging through the latest astronomical telegrams, the astronomer notices that a new asteroid has been spotted by a colleague in Spain earlier in the week and decides to begin his leisurely evening of star hopping by taking a peek at this newly found member of the solar system. He manually skews the telescope to his chosen subject for the night, opens the back of the camera to insert a sensitive photographic plate, and prepares to sit at the eyepiece of the guidescope carefully adjusting the telescope's rate of motion to accurately track the sky.

Or so goes the popular view of an astronomical career.

In the early part of the century, that picture may even have been a reasonably accurate representation of reality. Today, however, it is nothing more than an appealing fantasy. Modern astronomers come from all walks of life, and in recent years, 20 percent of Ph.D. recipients in astronomy have been women. While still a small percentage, it is double the percentage of women who receive Ph.D.s in physics. Unlike the romantic vision presented above, astronomers use computers in every aspect of their work, not only to control telescopes but also to record and process data. Modern electronics (e.g., CCDs; see Chapter 2) have given astronomers amazing instruments far more sensitive and flexible than either photographic film or the human eye, though not without their own limitations. And many fundamental astronomical results, such as the discovery of an expanding universe, detection of common elements in the sun and other celestial objects, and measurements of the temperature and density of various objects and regions in space, are not derived from optical images at all but from spectroscopy, requiring extensive instrumentation and careful analysis.

These days, astronomers also find work in nonacademic settings (about 20 percent, according to a recent American Institute of Physics survey—see Chapter 8). NASA and its contractors hire astronomers to support space missions. Many of these missions gather astronomical data and therefore require trained astronomers to decide the ways in which the data are taken and interpreted, to oversee the scheduling of the instruments, and to generate publishable results. Some NASA and ESA missions study the Earth's local environment and even the Earth itself. The data gathering and processing in these studies call for methods similar to those used by astronomers, and so astronomers often are employed even in a variety of space missions that study objects other than "the stars."

A small fraction of astronomers find employment within the U.S. military. The navy and air force are particularly interested in research that can be accomplished by well-trained astronomers. Industries involving communications technologies, which rely on the passage of electromagnetic radiation (often at radio frequencies) through space or the Earth's atmosphere, also have need for astronomers. With an extensive training in the generation, propagation, and detection of electromagnetic radiation, astronomers can work in a variety of physics-oriented careers, such as laser research and microwave propagation. The daily work of the adult astronomer is frequently very different from the life he or she imagined as a child looking through a backyard telescope.

Due to budget restrictions and an overabundance of astronomers interested in tenure-track teaching and research positions, other astronomers may take on a variety of nonresearch jobs. Some working astronomers with experience in computer programming, for example, are finding employment opportunities with Wall Street firms or large industrial corporations. The rise of the dot-com economy in the 1990s expanded the number and the nature of companies in which astronomers (many of whom develop considerable computer talent along the way to their Ph.D.s) have found work. Its recent unraveling may provide a larger pool of applicants for astronomy positions in the coming years. Creating and maintaining Web pages for their graduate departments or observatories, astronomers discover they often have a set of high-tech skills that are desired by computer or software firms. System management skills, the organized design and operation of computer systems, are also part of the package of alternative skills astronomers often possess.

In the course of their education, many astronomers become talented public speakers and educators, having given many talks about astronomy to the public or having taught classes as graduate teaching assistants. These skills are useful in a wide variety of careers and are especially advantageous in corporate management. A small number of scientifically trained individuals find careers in the public service arena, both in government and with organizations that interact with the government. All major universities have government relations offices, and most corporations and nonprofit organizations do as well. Astronomers well versed in public affairs find they can fit readily into a government relations career, thanks to their technical skills and ability to begin a task even in the absence of ground rules. Such, after all, is often the nature of scientific research.

Although a modernized version of the romanticized scenario of our first paragraph still exists for a small number of astronomers around the world, it is no longer the normal standard life. Astronomers, like members of many professions, are finding they must learn and develop a wider variety of skills to find a challenging and fulfilling career. The good news is that they are taking up this challenge and moving into rewarding positions across industry and the public sector, as well as in more traditional academic regimes.

In this chapter, we will outline the areas in which astronomers currently work and provide four short vignettes from individuals actually working in these areas. We will also discuss results from the American Institute of Physics workforce surveys as they apply to astronomers.

TRADITIONAL CAREERS

A traditional astronomy career begins with undergraduate education. Astronomers usually complete undergraduate degree programs in physics or, in some cases, astronomy. The rarity of undergraduate astronomy degrees is simply a reflection of the small number of universities offering such degrees. According to a 1998 American Institute of Physics (AIP) census, 762 universities offer physics undergraduate degrees, while only 61 offer an undergraduate astronomy degree. Occasionally, people enter astronomy from other courses of study, such as mathematics or engineering, but this is rare.

An undergraduate degree in physics or astronomy provides a good foundation for a future career in research astronomy. Astronomers must understand the laws of physics and how matter and energy interact. They must be able to understand fundamental theories of classical mechanics, electricity and magnetism, and quantum mechanics and calculate outcomes based on these theories. For observers, a thorough understanding of electronics, optics, and computer programming may be necessary. An undergraduate physics degree fulfills many of these needs and in most cases adequately prepares students for graduate study in astronomy or astrophysics.

Astronomers also receive a firm grounding in mathematics, including advanced calculus and differential equations. Courses in probability and statistics are also essential. Mathematics is the language of science, and astronomers routinely use advanced mathematics in the course of their research.

The next step in the educational process is to attend graduate school to earn a master's degree, a Ph.D., or in some cases both. During this period of their education, astronomers take advanced classes in astronomy and physics and, occasionally, mathematics. They also begin carrying out research under the supervision of a professor. This combination of advanced courses and research is critical because it serves both to fill in knowledge gaps and to initiate the astronomer into the rigors of professional life and to begin the investigation of open-ended problems.

Graduate programs in astronomy and astrophysics are challenging, with students often taking most of the classes required of physics Ph.D.s in addition to specialized courses for astronomers. Many individuals decide not to complete the Ph.D. but instead obtain a terminal master's degree and seek work within astronomy or in other related fields. Sometimes these professional master's recipients obtain employment in the defense industry or in support staff positions at observatories or with NASA contractors. These days, many now pursue careers in the wider business and industry sectors.

One of the fundamental requirements of the Ph.D. is to initiate and complete a course of independent research, which results in a formal dissertation that may subsequently be published in one of the professional journals as a research article or series of articles. This project often consumes large amounts of time and can mean that the degree process will take much longer than the typical 5.5 years beyond the bachelor's degree, according to an AIP Enrollment Survey. It is not uncommon to meet graduate students who are in their eighth or later year of graduate study. During this time, some sort of financial grant, either made to a research adviser or directly to the student, is usually essential for support, since paid graduate teaching assistant positions typically lapse before a student can finish his or her graduate degree.

The competition for the limited number of individual supporting grants (e.g., from the National Science Foundation or NASA—see Chapter 8) can be quite intense, and most students end up getting their support from their adviser's research funding. This funding picture places some constraints on the type of work most graduate students can perform for their Ph.D. Most often, their dissertation research is very closely related to that of their adviser.

During the 1997–1998 academic year, U.S. astronomy departments granted 192 bachelor's degrees, 29 terminal master's degrees, and 116 doctoral degrees. The number of doctoral recipients is slightly less than in past years (e.g., 133 in 1994–1995), indicative of a trend that may be related to a general decline in undergraduate physics and astronomy degrees awarded during the decade of the 1990s, as noted by the AIP.

To be sure, many other career tracks offer greater financial reward with less time spent in the educational process. It is interesting that, in the late 1960s, about 6,000 physics bachelor's degrees were awarded annually, while in 1997–1998 the number awarded was only 3,821. This trend may be related to the rise of computer technology, providing a new, expanding, and often highly lucrative career track for scientifically curious individuals who might otherwise have enrolled in physics or astronomy courses of study.

After obtaining a Ph.D., about 75 percent of astronomy graduates move on to postdoctoral research positions. These range in length from one to five years, with the average being three years. Postdoctoral positions may be based at a university, working with a professor, or at a national observatory or laboratory. Some positions overseas are also available, such as with astronomical institutes in foreign countries (Max Planck Institute in Germany, for instance), with U.S. observatories located overseas (such as Cerro Tololo in Chile), with foreign observatories (like the Anglo-Australian Observatory), or with foreign universities (including, for example, Cambridge). "Postdocs" are typically renewed annually, although multiyear appointments are also available. According to the AIP Initial Employment Follow-up Report for 1997 graduates, the mean annual income for U.S. postdoctoral positions was $36,000. For the sake of comparison, the average salary for individuals graduating with only a bachelor's degree in astronomy and working in industry was $38,000 in 1998. Clearly, astronomers are not primarily motivated by financial gain.

According to the 1997 AIP Employment Follow-up Report, about one-third of astronomy Ph.D. recipients found their way into permanent positions directly out of graduate school. Of this 1997 group, about 52 percent found work—permanent or temporary—in traditional academic settings. This environment, which can provide a great deal of freedom to the scientific researcher, is also a challenging one. Academic researchers must perform their own research, write grant proposals, and obtain some form of funding for their research activities. They also teach at both the undergraduate and graduate levels, serve on committees from the departmental level to university-wide panels, serve on proposal review panels, and often travel to meetings to present the results of their research. To succeed, true dedication to the field of research is a prerequisite. Typical salary levels for academic professors/researchers range from the mid-40s for the entry-level faculty members to above $100,000 for senior professors (AIP Employment Statistics Report).

Despite the relatively small number of permanent positions available to astronomers nationwide, people continue to pursue astronomy as a career. The number of Ph.D. recipients each year hovers at or above the 175 mark. The American Astronomical Society publishes a Job Register, which announces each month open positions in the field of astronomy or such closely related sciences as solar physics. Over the past four years, the number of jobs advertised has increased from about 300 per year to nearly 600. The jobs range from postdoctoral positions to tenure-track faculty positions.

With a stable graduation rate and an increasing (though still modest) number of jobs available, many more people may be able to pursue a traditional career in astronomy. However, a large fraction does choose to pursue career tracks outside of the traditional one. Although these positions are quite diverse, the generic term "industrial position" is often applied to them collectively. The more meaningful phrase "non-traditional astronomy career" would be more appropriate for any career path that involves an astronomy education but culminates in a job where astronomy does not make up the day-to-day work.

RANGE OF NONTRADITIONAL ASTRONOMY CAREERS

As just discussed, a traditional career in astronomy begins with a firm education in physics or astronomy and advances through a graduate degree, and a postdoctoral position and ends with an academic tenure-track position. Although difficult to determine exactly, it is now estimated that fewer than 10 percent of people who begin undergraduate education with the intent of becoming astronomers actually succeed in completing the traditional route. At first glance, this may seem like a waste of useful talent, but, as we have described, the education needed to perform research astronomy can serve as an excellent foundation for a wide array of careers. The value of an education in astronomy is reflected in the unemployment statistics for the profession. The unemployment rate for astronomy and physics Ph.D. recipients in 1999 was less than 2 percent—approximately one-third that of the general population. The mean salary levels for Ph.D.s working in nontraditional astronomy careers is higher than for those working in academe. For 1998, the mean industrial salary was $84,000, while the overall mean salary for university-employed doctorates was about $69,300 for a 12-month contract and $63,000 for a 9- or 10-month contract.

The sheer diversity of positions that astronomically trained individuals find is overwhelming. Among the authors' colleagues trained in astronomy are, for example, a chocolate importer, financial programmers, Web site designers, a few environmentally oriented workers, a staff member for a major international Christian missionary organization, Peace Corps volunteers, computer programmers, a concert musician, business consultants, industrial managers, a science museum director, and an actor. Obviously, a science degree is not a prerequisite for many of these jobs, but the skills learned while pursuing a science career can be applied with success in a wide variety of career situations.

The basic skills learned while pursuing a science degree are varied. Among the first is critical thinking. Scientists must judge from observational evidence whether or not a hypothesis is correct. This can be directly applied in the business world. Are the current marketing expenses large enough to produce greater sales? How can this be tested?

Experimental design is learned by all scientists and can help to answer tough management questions. Scientists also learn simply to start projects and see where they end up. Sometimes there is not enough information available at the start of a project to predict where it will go. The same conditions hold true in science most of the time and, often, hold true in the business world as well.

Astronomers learn a wide variety of software applications, programming languages, and data management skills, which are easily applied to the world of computer science or information technology. They are experts at image processing and analysis and can, therefore, find work in the medical-imaging industry or in industrial-imaging application work.

Finally, astronomers—and scientists in general—often have excellent communication skills. The popular vision of the quiet, nerdy kid from high school seldom describes the product of a graduate education in astronomy. Constant oral presentation of results takes place during graduate school and even as undergraduates. Writing skills are necessary to obtain telescope time and grant funding. Concise scientific writing is required for research articles and professional communications. All of these presentation skills, especially the writing skills, are very necessary for successful nontraditional careers.

Perhaps the best way to gain some insight into the world of people who have started out working directly in astronomy and then expanded into other careers is to share some vignettes describing individual career progression. The following four pieces were originally published in the American Astronomical Society Newsletter in 1999 and 2000 and are reproduced here with permission of the authors.

José Navarro: An Astronomer in the Oil Industry

Three years ago, I had a change of careers. After marrying a Norwegian, we decided to move to Norway. My particular research interest—pulsar radio astronomy—did not seem to be popular in this northern country, so I started to look for alternate work opportunities.

It just happens that our city, Stavanger, has long been the oil capital of Norway and I was able to quickly find compatible employment in data processing for oil exploration. Since my transition was successful and I am enjoying my new career, I thought I would share my story with other astronomers thinking of alternative careers.

I was at the Very Large Array radio telescope in my second year as a postdoc, really enjoying myself while studying pulsars, but also thinking of the years ahead. Being an astronomer requires involvement in disciplines from astrophysics to electronics, computers, software, data management and observation, in addition to teaching and some level of management. All of us have some experience in these fields and skills that could well be applied to other endeavors with similar requirements, be they in academia or industry. The question, of course, was whether I should work hard to succeed in academia, or whether I should work hard to succeed in industry. After some thought, I decided to try industry.

When I made this decision, I did it with the intent of returning to astronomy if I wasn't happy after one whole year. Yet, after three years, I am still happy! I have had to learn a lot about geophysics in my new job, but the challenge has been adapting to working in a multinational corporation.

I started in a small group doing commercial processing for seismic exploration, where we generated images of potential oilfields using data acquired by seismic vessels in the Norwegian and North Seas. In some ways, this was not very different from observing at a telescope and then reducing the data back home to form images or spectra. In fact, many of my image processing skills and even some of my experience with inversion methods came in very handy.

I now manage a small group that also does special imaging in seismic exploration, but under an international contract and based in England. When I made the move to England, my wife was able to transfer within her company to a different office. We were probably lucky in this respect and this points out another difficulty in the real world for both academically and industrially employed people.

In my new job as a manager, I am still doing some production work but my job is more complex. I must win more contracts, carry all projects to a happy and timely completion, and keep my group at the forefront of technology in our particular field. The challenges are to provide solutions to the specific requirements in each contract, to properly forecast what each project will entail, to find sufficient computing power and to keep costs down. Satisfaction comes mainly with a happy client and with a net profit, and more so when a project is technically challenging.

Being a manager may not sound very appealing to someone doing research, but in truth, it exposes me to more projects and situations. It offers me the possibility to learn by concentrating on the bigger picture, and yet it still allows me to roll up my sleeves to solve specific technical issues when they arise and my help is needed. Sadly, from a business point of view, I find these crisis periods quite enjoyable because I can return to programming, problem solving and creative thinking of the kind that I thrived on as a graduate student.

Working in a large international company has some advantages: training is often provided when needed, resources and expertise usually exist somewhere in the company and there are internal career opportunities. Jobs, however, are not secure and at least in oil exploration, redundancies are linked to the price of oil. Another source of frustration is that profit drives most work and, as a result, there is less possibility to dedicate time and resources to following up technical ideas that are interesting but not directly applicable. Even so, overall my experience has proven very inspiring and rewarding and I do not plan a return to academia.

Sometimes people ask me if a Ph.D. in astronomy helps in a different industry. The answer is both a clear YES, in that it shows you are able to find original solutions to problems and work independently to implement them, and NO, in that none of the actual work for your thesis will probably be used. Nevertheless, the hard work is not wasted because, along the way, you learn new tools, how to find resources, how to solve smaller problems and how to make progress. In the end, it is not just knowledge that counts, but also experience, resourcefulness and versatility. Being able to identify challenges and then finding direct, creative and cost effective solutions is what generates success.

Roger L. Mansfield: An Astronomer in the Air Force

I began my career in 1967, entering the Air Force as a second lieutenant. I performed weather satellite orbital analysis for the Defense Meteorological Satellite Program. I then taught mathematics at the US Air Force Academy and, after serving a total of seven years in the Air Force, worked for 21 more years on Air Force space systems developmental projects.

I originally earned my BS degree from the University of Cincinnati and an MA in mathematics from the University of Nebraska at Omaha. I assisted with tracking data reduction for the Earth 1 and Earth 2 flybys of the Galileo spacecraft, for the Mars Observer launch and Earth escape, and for the NEAR launch and Earth escape. Currently, I publish educational materials that are custom-prepared for science teachers and also teach astrodynamics and numerical methods to engineers at Lockheed Martin's Astronautics Waterton Canyon facility (builders of Mars Pathfinder, Global Surveyor and the Cassini spacecraft).

Although the route to astronomy is commonly through academia, I found that by serving my country in the armed forces, I could pursue my interests in relative comfort. The Air Force, Navy and Army all need recent physics and engineering graduates at every level. And they will continue your training while you work.

You don't have to have participated in a Reserve Officer Training Corps (ROTC) program as an undergraduate to find your way into the officer ranks. I applied for Air Force Officer Training School (OTS) during the Vietnam era after earning a BS in chemistry. After three months of OTS, which consisted mostly of classroom training (but yes, there was marching and physical training, too), I was commissioned as a second lieutenant and then sent to special service schools that provided advanced training in space operations and orbital analysis.

In my seven years of active duty, I developed orbital mechanics software for military weather satellite operations and taught mathematics at the U.S. Air Force Academy. The contacts I made while on active duty led me to a 21-year career in the civilian space industry, developing astrodynamic algorithms and software for artificial Earth satellite tracking and space surveillance. The mathematical foundations here are pretty much the same as for cometary, minor planet and interplanetary space probe orbit determination.

The "nerve center" for military space operations is US Space Command, with headquarters in Colorado Springs, Colorado. This "unified command" has Air Force, Navy and Army components, so it is possible today for a young officer to do a tour of duty in military space operations from any one of the three major service branches. You could work in the Space Defense Operations Center (SPADOC), keeping track of all space activity and maintaining a catalog of orbital elements for all objects in Earth orbit (including a wrench and a glove!) or you could be involved in the command and control of military weather, communications, global positioning, reconnaissance, or early warning satellites.

My most important role as a civilian space professional was to help design and build the SPADOC 1982–1995. Some special assignments that I had were to assist in flyby tracking operations for the Galileo spacecraft's Earth 1 and Earth 2 flybys (1990 and 1992, respectively), and to assist in reducing tracking data on the NEAR spacecraft's Earth escape trajectory of 17 February 1996. Algorithms that I had developed especially for Earth flyby tracking were implemented in SPADOC's software and I was able to publish my work in the *Journal of the Astronautical Sciences* ("Algorithms for Reducing Radar Observations of a Hyperbolic Near-Earth Flyby," April–June 1993).

The financial security that resulted from my saving and investing good parts of my military and space industry salaries over 28 years made it possible for me to retire early and to pursue my passion for orbital mechanics with my own computers. In addition to the traditional compiled languages FORTRAN, Pascal and C, I use MathCad and its new programming capabilities. Over the past three years, I have also taught courses in astrodynamics and numerical methods via a part-time appointment as an assistant professor at the University of Colorado Springs.

My success could be anyone's success. Serving in the military as an officer gave me a chance to perform cutting edge work and increase my knowledge and skills. A degree in physics or astronomy is the key qualification. You must also be in good physical condition and be able to work effectively in a team environment. It helps to realize that military service is service to your country, i.e., service to your fellow citizens. The timing of your transition from the military to a civilian career could be pretty much up to you, as it was for me.

Doug Duncan: A Modern Planetarium Astronomer

Over the past several years about a dozen new permanent astronomy jobs have been created combining research and teaching or outreach to the public. There may be more such jobs in the future, but the people in these innovative positions need the understanding and support of the astronomical community if they are to be successful. I believe this success would benefit us all, so I will describe these positions, their benefits and their risks.

In the summer of 1991, while preparing for my tenure review at STScI, I received a surprise call from the retiring and new Directors of the Adler Planetarium offering me the Assistant Directorship of the greatly expanding Planetarium. I politely declined, explaining that I believe research and teaching belong together, and that a big problem with Planetariums is that they don't give their astronomers any time for research. Consequently, they fall behind the times and miss out on the astronomy most people find exciting. After months of discussion between the new director, the University of Chicago (UC), and myself a position was created, which called for me to oversee the Education and Astronomy Departments of the Planetarium, and to serve as Associate Professor at UC, with reduced teaching load but full expectation of active research. I was then asked to design and justify more planetarium-astronomer jobs.

Why is it important to have active astronomers in Planetariums? Planetariums do enormous public outreach and represent our field in the eyes of most of the public. The message which gets presented there is how most people view all astronomers. Have you been to a Planetarium recently to hear what messages are being conveyed?

From the Planetarium point of view, hiring an active astronomer should bring many benefits. These include an increased talent pool from which to recruit, greater variety in the programs that can be presented, and greater enjoyment and excitement experienced by visitors when they are given access to new discoveries in a timely and understandable way. Adler trustee and UC professor Bob Rosner put it this way, "If you allow a person to do a certain amount of research, as well as teaching, you can attract a different kind of person. That person tends to be highly motivated and excited about his or her work." Such scientists can make sure that content is current, including discoveries such as new planets, supernovae and cosmology. Active astronomers can present science as a process. They know that science is fun to do, and can design programs that allow the public to be active, not passive, astronomy learners. They can use their thorough knowledge to present simpler explanations. Being an expert doesn't necessarily make you a good explainer, but people who don't know a topic well usually skip it or dumb it down. Researchers usually have up-to-date knowledge of the technology of a discovery, which may be lacking in Planetarium staff. In my case, I introduced ideas such as using the Internet, hiring the first computer system manager, and performing the first multi-lingual translation (done by using email to talk to astronomers in other countries).

What are the risks? A newly hired astronomer may find that some review panels will discriminate against those who work in Planetariums. This is unfair: A good proposal from any institution ought to have the same chance for funding, telescope time, or computer time. Nowadays there are excellent scientists at many institutions, not just a few. Generally, this attitude seems to be improving. A surprise to me was how often Planetarium staff have a poor perception of astronomers. Descriptions like "arrogant" and "poor communicator" come to mind. An active astronomer may be a good teacher, but a Planetarium will challenge anyone's ability to communicate to a diverse audience. In a Planetarium, diversity means grandma, the kids, some inner city students and people on a date. To be effective at a Planetarium, real-world teaching and teamwork skills are required, which often are not taught in graduate school. Also, more astrophysics is done in major projects, where communication skills are important. Graduate schools serve their students when they prepare them for this. Prompted by the AAS [American Astronomical Society], many graduate schools have posted on the career paths of their Ph.D. students on the World Wide Web. The diversity of positions is impressive, and many of them require good communication and teaching skills. The University of California, Santa Cruz, did an especially good job of surveying its graduates from several decades. As part of that survey, students were contacted and asked what they wished they had better prepared for in graduate school. "Teaching" was one of the most frequent replies.

Another surprise to me was that a part of the Planetarium community is often uncomfortable with modern astronomy concepts and with change, and wants mainly to teach constellations and the seasons. An insidious risk is that the time an astronomer spends doing research or at conferences will be considered "wasted" by some Planetarium staff, who tend to travel much less than academics, compounding the insularity of the field. Only if Planetarium management stresses the importance of this will the astronomer not be penalized for it.

Astronomers, especially research astronomers, should consider becoming members of Planetaria staff. The rewards can be numerous. Often a more relaxed pace to the workday, greater interaction with the public and still some time for research. Overall, working at a planetarium provides a balanced astronomical career.

Andrea Schweitzer: An Astronomer in Industry

After I graduated from the University of Wisconsin in 1996, I chose to turn down the short-term astronomy job offers I received in favor of a position with Honeywell. Since then I have gone through industry layoffs, done contract work for Hewlett-Packard, and am currently the project manager for new product development at Cytomation, Inc., a mid-sized start-up company that builds instrumentation for biotech research.

There are obvious advantages to working in industry: higher salaries, 40-hour work weeks (at least in theory), and more opportunities available.

The leap from the Ivory Tower into an industry cubicle is a significant transition, not to be undertaken lightly. Writing a résumé for industry is a straightforward exercise compared to the complex emotional transition that takes place.

When the emotional side of an industry job search goes unacknowledged, it may hinder a job-seeker's ability to make the best use of their time and energy, write a good résumé, do networking, interview effectively, and enjoy an industry job. These are tough consequences, and oftentimes there is scarce recognition of the importance of emotional transitions or support in dealing with them. It is crucial for individuals and the astronomical community to address these emotional issues.

Of course, no one's emotional transition will be identical to mine, but I have identified three issues that hit me the hardest, and which I think others would have in common with me.

First, an industry job search requires grieving. I became an astronomer because I loved it more than anything else, and consequently it was a great loss to leave. A second emotional transition was my loss of identity. People were thrilled to talk with me about being an astronomer, but they don't react to engineers with as much enthusiasm. Of course, I will always consider myself an astronomer, even if I don't earn my living at it! Third, I have lost much of my life's work. When I wrote my industry résumé, the hardest part was hitting “cut” for the details of my years of research, knowing there was nowhere to ever “paste” it back in again.

However, once you move through the sadness that accompanies your departure from professional astronomy, there is room to enjoy the new opportunities industry offers. Peter Stetson once said to me that there are interesting problems waiting to be solved everywhere. I agree: the problems I’m working on now are more down-to-earth (literally!) but are still interesting.

However, I like my life in the business world, and believe that it suits me better! The work environment is very different from academia. Although companies can have a variety of climates, here are some of the benefits I’ve found:

- People are hired not only because they are smart, but also because they work well with others.
- There are more opportunities to be given responsibility and to move up quickly.
- I’ve found it to be a better environment for women, with less sexism.
- Companies frequently evaluate their processes, and talk about how employees can work more effectively together.
- And of course, there is more money and better benefits!

One great advantage I discovered during my recent layoff is that in industry, the senior people who are in roles equivalent to tenured professors are often the most sensitive and supportive regarding job hunting. Looking for a new position from within industry has been much easier than trying to get the first job after grad school. This is partly because I have more experience, but also because I had numerous older men being emotionally supportive, and offering networking and helpful advice. Because the senior, better-paid employees are often laid off first, they know that they could be job-hunting tomorrow, too. While it is painful to see older employees laid off, industry does have a more level playing field.

There are many differences between academia and industry, and it’s important to make sure you have the right skills, both personal and technical, before making a career change. Many astronomy departments and the AAS have been considering how to help graduate students acquire marketable skills without compromising their graduate training or adding extra coursework. Towards that end, I have compiled a list of skills which are the most helpful to me today, and which can be developed during graduate school.

My current boss said that he’s fired more Ph.D.’s than any other type of employee—not for lack of technical skills, but due to “perfection paralysis” (getting hung up trying to perfect minor details in a project while missing its broader scope), lack of interpersonal skills, and difficulty adapting to the industry environment. It is much easier to teach a good employee another technical skill than to change someone's personality! Therefore, I put interpersonal skills at the top of the list that industry is looking for. While graduate school focuses primarily on research skills, I found I developed useful people skills along the way, especially working as a Teaching Assistant. These skills include:

- Listening (to understand what your boss or customer wants)
- Teaching (helpful for presentations and sales, customer support positions, and in explaining technology to non-technical staff)
- Balancing working alone and as part of a team (being a self-starter who is able to work independently, but also knowing when to ask for help and how to work well on a team)
- Tact and diplomacy. Ironically, the day after I completed a draft of this vignette, I met with my boss and the president of the company for an informal performance review. Their harshest criticism of me was the need to improve my people skills, so don't underestimate the importance of this!

My managers also stress that scientists must shift their thinking from an academic to a business mindset. Such skills include the ability to:

- See the bigger picture beyond your current work
- Realistically estimate schedules and stick to them
- Change the focus of your project quickly and willingly
- Juggle many things at once

Doing dissertation research, especially while having other teaching research or computer support responsibilities at the same time, can develop these skills.

Many technical skills you learn as a scientist are in great demand by companies. Skills that can be acquired during a graduate program and then applied in industry are:

- System administration and programming
- Data analysis and summarizing results
- Hardware/software testing and troubleshooting
- Ability to do "back of the envelope" calculations
- Physics background (which is the foundation for engineering)

Also, don't underestimate the value of being able to learn quickly. Business preferences for software knowledge changes rapidly. The ability to learn new things quickly is ultimately more important than any one particular skill.

Finally, good written and verbal communication is important for success in any position. I found that highlighting these skills from the scientific world can be useful for an industry résumé:

- Grant/proposal writing
- Communicating technical information to various audiences
- Technical writing

When I was preparing for my career change to the private sector, I found that my university's School of Engineering had a career center with excellent resources on how to write an industry résumé, research companies, and prepare for interviews. Unfortunately, as an astronomy student within the School of Letters and Sciences, I was not allowed full use of the career counseling. I recommend that astronomy departments become aware of and utilize university facilities like an engineering career center, and ensure that all students have access to those resources.

While switching to industry is a challenging process, the good news is that companies are eager to hire people who combine technical backgrounds with good interpersonal skills.

CONCLUSION

These four vignettes provide a brief glimpse into the careers of individuals who began working in pure astronomical research and branched out into other areas, some more traditional than others. What is evident is that none of the people waited for change to come to them but took advantage of their situation and skills to launch out onto an alternate career path. They enjoy an exciting work environment, financial freedom, and a more constrained work environment. Astronomers can and do succeed in very different career tracks than their precise training has prepared them to follow.

CAREER RESOURCES FOR ASTRONOMY AND AFFILIATED FIELDS

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Online Resources

American Association for the Advancement of Science Career Web Page. http://nextwave.sciencemag.org/. Discussion groups, advice, job listings, and timely articles.

American Astronomical Society Career Web Page. http://www.aas.org/career. Links to resources, job listings, and so on.

American Institute of Physics Career Services Web Page. http://www.aip.org/careersvc. Links to resources and employment statistics.

Career site for Ph.D.s. http://www.phds.org/

High Tech Jobs Databases. http://www.brassring.com/ and http://www.dice.com/

Mentoring for Women in High-Tech Careers. http://www.mentornet.net/

SUMMARY

Astronomers rarely spend every waking hour at the working end of a telescope. Data collection and processing have been digitized, and most astronomers actually sleep normal hours these days, except for the occasional observing trip. Overall, astronomically educated individuals enjoy a low unemployment rate and can obtain a high level of monetary compensation, although not necessarily in academia. The relative freedom of academic jobs is offset by the lower compensation typical in these positions. Increasingly, astronomers are finding careers in alternate areas such as business, industry, finance, or computer technology. Their education, based on a foundation in physics and mathematics, can prepare them adequately for a wide variety of careers. The job situation for astronomers appears to be improving, with more jobs available now than ever before. This improvement is likely to continue in the short term, but since a large fraction of pure astronomical research is funded by the federal government, the current ease in finding employment could change over relatively short time periods.

Modern technology has finally caught up with our ambition to understand the farthest reaches of the universe. There are great opportunities in many different fields for those willing to endure—or prepared to enjoy—the years of training and preparation to become modern astronomers.

Chapter Eight

Statistics on Careers and Research and Development

Since its beginnings, astronomy has received funding either from governments or from wealthy patrons. The earliest astronomers (see Chapter 3) were employed by their rulers to keep time and look for propitious omens. Kepler, Galileo, and others received private funding, while astronomers like Tycho Brahe received funding from the state—for him, directly from King Frederick II of Denmark. Although a few astronomers have supported their research with their own personal wealth (the American Percival Lowell comes to mind), such lucky individuals are very rare. Today, the bulk of professional astronomy is funded through governmental support, with a few recent exceptions—the Keck telescopes on Mauna Kea and the SETI radio array (the Allen Telescope Array), for instance.

The U.S. government funds both space-based and ground-based telescopes. The Hubble Space Telescope and the Very Large Array are two of the most famous examples in these broad categories. A National Research Council Report titled *Federal Funding of Astronomical Research* highlights recent funding patterns and indicates that the National Science Foundation, the only government agency tasked with supporting basic research, has gradually ceded to other sources its role as the prime funding agency for astronomical research. The National Aeronautics and Space Administration space science research budget has grown 34 percent over the past 10 years to fund 65 percent of astronomy research carried out in the United States.

In part responding to this report, the administration of George W.

Bush has established a blue ribbon panel, the National Research Council's Committee on the Organization and Management of Research in Astronomy and Astrophysics, or COMRAA, which reviewed the funding of astronomy and astrophysics research during the summer of 2001. The panel was specifically tasked with considering the implications of combining NSF's astronomy funding with NASA's space science research efforts. The committee released its findings on September 5, 2001, and the executive summary of this report is included in Chapter 4.

Although the committee did not recommend merging NSF's astronomical sciences division with NASA, it produced a number of recommendations that will have a long-term impact on how astronomy is carried out. The most important recommendation outlines the formation of an interagency planning board for astronomy and astrophysics. This panel would receive input from the agencies that do astronomical research (mainly the National Science Foundation, National Aeronautics and Space Administration, Department of Defense, and the Department of Energy) and receive input from the community. The panel's main job will be to coordinate the research activities of the member agencies and prepare an annual integrated strategic plan for astronomy and astrophysics. Only time will tell if this coordinated approach will help astronomy receive more funding overall. The concept of a coordinated plan is necessary; how it is implemented will determine its effectiveness.

This chapter summarizes recent data related to both the funding of astronomy in the United States and education and workforce statistics for the field. Original sources are indicated in the text, along with notations of sources where updates can be obtained.

Despite its broad popularity with the public, astronomy research is carried out by a relatively small number of people. The American Astronomical Society (AAS, Web site: http://www.aas.org), the oldest professional astronomy society in the United States, has only about 5,500 U.S. members. The International Astronomical Union (IAU, Web site: http://www.iau.org), the international governing body for astronomical standards and organizer of important international conferences, boasts only 8,300 members worldwide. Although these numbers seem small, the number of professional astronomers was far smaller just a century ago. At the first meeting of the AAS, in 1899, only 50 astronomers were in attendance. Today, AAS meetings routinely host 2,000 or more participants (David H. De Vorkin, *The American Astronomical Society's First Century*, 1999).

Because the bulk of the research carried out is funded through governmental sources, it should not be surprising that the number of astronomers tracks quite closely with the amount of federal funding available. The American Institute of Physics surveys the physics and astronomy workforce, undergraduate and graduate students, and astronomy and physics university departments. One of the striking results from a recent study of first-year graduate students is that the number of students entering physics or astronomy graduate school has been decreasing steadily and reached an all-time low in 1997. What this statistic bodes for the long-term health of astronomy research is not clear, but by tracking trends in workforce changes, policy makers can make informed decisions about funding levels and federal agency support.

FEDERAL FUNDING OF ASTRONOMY

The U.S. government funds astronomy and astrophysics mainly through NASA and the NSF, with budgets for research and equipment totaling more than $2.6 billion (FY 2001). Smaller amounts of funding are provided by the Department of Energy, Smithsonian Institution, the Department of the Navy, and the Department of the Air Force, which total less than $100 million each year (NRC, *Federal Funding of Astronomical Research*, 2000), with $30 million from the Department of Energy, $20 million from the Department of Defense, and $25 to $30 million from the Smithsonian Astrophysical Observatory. In sum, these additional sources of governmental funding approach the current level of NSF support. Funding for these agencies is provided through appropriations made by the U.S. Congress.

NASA and NSF receive their funding through the Veterans Administration, Housing and Urban Development and Independent Agencies Appropriations Bill (VA-HUD). As is clear from the title, this bill funds many agencies, primarily the Veterans Administration and the Department of Housing and Urban Development, and NASA and NSF funding is often preempted by other priorities. Nevertheless, astronomy remains a relatively well-funded science.

Astronomy funding from NASA and NSF falls into four broad categories, as defined in the recent NRC report *Federal Funding of Astronomical Research*:

> Operations: This category includes operations expenses for NASA space missions and the operating costs of ground-based telescopes run by both NSF and NASA.

Instrumentation: This includes support for construction of instruments that detect electromagnetic radiation (light) in some form as well as technology development at both agencies.

Science and Analysis Support: This category includes support for the actual observations and data analysis at NASA, the individual investigator grants at NSF, and the astronomical theory program at NASA.

Construction: This category contains funds that enable the actual construction of major facilities on the ground and design, development, and construction of space-based observational satellites.

NASA and NSF subdivide this funding into different accounts within the overall agency budgets, the details of which, for the 1990s, may be accessed online at http://books.nap.edu/books/0309071399/html/index.html.

Past NSF Funding

One striking result of the NRC *Federal Funding of Astronomical Sciences* report is that, in real terms, NSF support for astronomy has decreased during the 1990s by about 5 percent in constant dollars. During the same period, the entire funding for NSF Research and Related Activites grew by 15 percent in constant dollars. For FY 1999, NSF provided about $7 million for instrumentation, $81 million for operations, $25 million for research, and $8 million for construction. The NSF construction amounts vary dramatically year to year as construction projects are initiated and completed. In 1991, for example, about $80 million was provided in a onetime funding event to construct the Greenbank Telescope now operational at the National Radio Astronomy Observatory site in Green Bank, West Virginia.

In addition to these amounts, the Mathematics and Physical Sciences (MPS) directorate, under which the Astronomy division (AST) resides, expended about $10 million for astronomy efforts. The Office of Polar Programs also supports astronomy, in 1999 at a level of $5.6 million. The division of atmospheric research provided approximately $10 million for astronomy-related research. In addition, the Laser Interferometer Gravitational-Wave Observatory (LIGO) completed construction in 1998 and began formal operations in 1999 at a level of $21 million per year. Finally, various other offices within NSF and undistributed funds within AST amount to about $1 million. The bottom line is that NSF provided about $150 million for astronomy research in FY 1999 (in constant 1997 dollars).

Comparing this level of support to inflation-adjusted figures for the decade of the 1990s shows that NSF support of astronomical research has remained relatively flat, with declines in the middle of the decade and occasional bumps in funding for facilities upkeep and construction. In 1990, the total NSF support for astronomy was $145 million (in constant 1997 dollars).

When adjustments are made for onetime expenditures related to construction, the overall support from NSF has declined by about 10 percent over the decade. Interestingly, this comes at a time when the field (in terms of numbers of astronomers who were members of the AAS) grew at a relatively steady pace. However, as outlined in "An Astronomical Career," later in this chapter, the number of graduate students beginning to study astronomy declined by about 10 percent during the 1990s. A one-to-one correlation between funding levels and graduate student enrollments is not to be expected, but the similar downward trends are probably related, since NSF funds a large number of students through grants to individual investigators.

Past NASA Funding

If you follow the news, you know that just about every issue of the *New York Times* and many editions of the evening news carry stories related to NASA and its astronomy and space science programs. Either reporting about its manned space flight program, explaining the trials and victories of the International Space Station, or simply presenting some new astronomical discovery, newspapers and television programs around the world give astronomy its due. NASA does not receive a large amount of government funding compared to other agencies. NASA funding, as explained in detail in Chapter 3, represents less than 1 percent of the total FY 2001 federal budget. Why, then, does this one agency have such a seemingly disproportionate impact on our daily lives? Perhaps because NASA and its programs help us to imagine and see other worlds that we will never visit and give us an outsider's perspective on our own planet. The pictures that NASA provides of the Earth, solar system objects, and distant stars and galaxies tell amazing stories—and the public can't help being fascinated.

The FY 2002 funding level for NASA is anticipated to be just over $15 billion. Although cheap compared to the Department of Defense budget, expected to be at least $325 billion in FY 2002, NASA's budget is scrutinized very closely by congressional appropriations committees. This year, an unexpected $4 billion overrun in costs for construction of the International Space Station will have a direct impact on the enacted funding levels for NASA's human space flight activity. Congress does not like unexpected overruns and has recently punished programs that overran their original cost estimates.

NASA funds astronomy research through its Office of Space Science (OSS), which is funded from the Science, Aeronautics, and Technology Account. According to *Federal Funding of Astronomical Research*, NASA's funding for astronomy has grown dramatically during the past 20 or so years. Because NASA frequently changes its accounting system, bringing in new budget lines and splitting, augmenting, or deleting other lines, it is extremely difficult to determine exactly how much funding has increased overall. However, most astronomy research is funded in two lines, which can be traced back reliably for a number of years. They are the Research and Analysis (R&A) budget line and the Data Analysis (DA) program. Funding of other items, like construction of scientific satellites and so on, is tracked in other budget lines. The *Federal Funding of Astronomical Research* report, the most reliable historical analysis of NASA's funding of astronomy, tracked these accounts over time and came to a number of important conclusions.

First, the amount of funding for R&A and DA between 1989 and 1999 increased by a full 50 percent in constant dollars. In 1999, about $90 million was allocated between these two NASA funding accounts, compared to NSF's 1998 research grant level of $26.4 million. This shows that funding for astronomy research by individual researchers comes mainly from NASA, which provides about 76 percent of the total available funding.

Second, NASA provides funds in its DA line to individuals who analyze data obtained with NASA satellite missions. More than one-third of this funding supports data analysis for the Hubble Space Telescope mission. In 1999, $31.6 million was distributed to researchers using data from HST. This total for data analysis work on the Hubble Space Telescope alone is larger than the entire NSF direct grants program, a discrepancy indicating that a large fraction of funding for astronomy research is tied directly to a *single* mission, the HST. Should HST stop working or fail catastrophically (and there have been recent scares with the gyros that maintain the attitude of the spacecraft), a large number of astronomers would suddenly find themselves without research funding support.

NASA also provides funding for theoretical research through its Astronomical Theory Program (ATP). The ATP has remained as a budget line available to individuals since 1987. Unlike the R&A and DA programs, ATP has declined in real dollars since its inception. In 1987, the program had a budget of $6.9 million (in inflation-adjusted 1997 dollars), while in 1999 it had only $6.14 million, a decline of just over 10 percent. Even with this decrease, the Astronomical Theory Program of NASA remains a very important source of funding for theorists and rivals the amount provided by the NSF for astronomical theory.

Implications of the Current Funding Situation

A major shift in the way astronomy research is supported has taken place during the past 20 years. NSF, formerly responsible for more than 60 percent of the total amount of individual research grants, now provides less than 30 percent. NASA has come to support over 70 percent of the total funding distributed to astronomical and astrophysical researchers.

This shift in funding has both good and bad consequences. Astronomers are more vulnerable to single mission failures, but the overall amount of funding available for research has grown. Should the Hubble Space Telescope fail, 30 percent of the funding available for research would suddenly dry up, and there is no safety net available. Perhaps NASA would find some other way to fund the researchers, but apparently no contingency plan is currently in place.

One might expect the shift in funding to influence the topics that research astronomers choose to study, following the money, so to speak. However, the committee that produced the *Federal Funding of Astronomy and Astrophysics* report compared the topics of research papers published currently with those of the past and found no measurable shift in the topics studied. Further, no statistically significant shift in the number of astronomers employed at universities, government labs, and federally funded research centers took place. The field has remained remarkably consistent in both topics studied and employment location over the past 20 years, despite the described funding shifts at the federal agencies.

It is likely that astronomers will continue to rely on government funding for the bulk of their research support and that NASA and NSF will continue to be the main sources for individual research funds. Since the funding distribution and methods have not resulted from a strategic government plan, but simply the year-to-year funding cycle, it is not surprising that shifts in funding priorities have taken place. In fact, they should be expected to continue, barring a forceful set of recommendations from the Office of Management and Budget, the

White House, or Congress. Astronomers will continue to be at the mercy of the vagaries of their source of funds. Recently, a few major private donations have enabled the construction of several large telescope projects. Examples include the one-hectare Allen Telescope Array SETI telescope being built by researchers at the SETI institute in California. This telescope is being constructed at a cost of $25 million, $11.5 million of which is being provided by Paul G. Allen, an investor and philanthropist. An additional $1 million has been donated by Nathan P. Myhrvold, former Microsoft technology officer.

AN ASTRONOMICAL CAREER

Although more astronomers are working today than ever before, their total numbers are still very small. By combining the total members of the major astronomical societies worldwide, we know that there are only about 10,000 working astronomers—roughly 0.002 percent of the world population, or 1 astronomer for every 5,000 people. For comparison, in the United States in 1998, there were about 100 doctors for every 5,000 people worldwide and about 130 lawyers (U.S. Bureau of Labor Statistics (http://www.bls.gov/).

Most working astronomers are located in the United States, Europe, and Japan. Many work for the various space agencies, such as NASA or the European Space Agency, either as contractors, grant recipients, or full-time employees. Some work at universities as professors or researchers. Another handful work at government laboratories like Los Alamos National Laboratories (LANL) in New Mexico and Lawrence Livermore National Labs in California. Still others work in a diverse assortment of professions not directly related to astronomy. There are astronomers working on Wall Street as consultants, programmers, and predictive modelers. Some astronomically trained individuals work in imaging technology or computer science. Others work at planetariums, with news organizations, or even as lobbyists or in the federal bureaucracy. Just because an individual trains in astronomy does not mean that he or she will end up working as an astronomer, although the majority (80 percent, according to the American Institute of Physics–American Astronomical Society AAS PHD + 8 survey) of astronomy Ph.D.s do.

The skills learned by astronomers can be applied to a wide range of scientific and technological problems. The detailed knowledge of electromagnetic radiation—how it propagates, how it interacts with matter, and how it can be detected, measured, and even redirected—is one of the most fundamental tools in the astronomer's skill set. The ability to manipulate digital images, to apply complex mathematical models or processing to images, and to interpret image data is another key component of the astronomical toolkit. These skills have wide application in medicine, telecommunications, remote sensing, and digital image processing. Astronomers are employable in a wide variety of professions, as the narratives in the previous chapter indicate.

In recent years in the United States, about 120 people have graduated with a Ph.D. in astronomy or a closely related science from 69 Ph.D.-granting institutions (AIP Recent PhD Survey, Graduating Class of 1997–1998). The same institutions awarded about 25 or so terminal master's degrees. About half of the degree-granting institutions are astronomy departments, and the rest are combined astronomy and physics departments or physics-only departments. Surprisingly, the number of bachelor's degrees in astronomy is roughly 200 per year, indicating only a slight attrition of students between the bachelor's and a terminal graduate degree, although it is important to remember that many undergraduate majors, including physics and engineering, successfully feed into astronomy Ph.D. programs. About one-third of those graduating with a Ph.D. in astronomy are foreign, and only about 20 percent are women. This percentage is about double the fraction of women earning physics Ph.D.s, which is currently around one-tenth of the total number of degree earners.

The American Astronomical Society, the professional society for astronomers in the United States, advertises about 600 jobs per year in its job register. The number of advertised positions is doubling about every five years (American Astronomical Society Annual Report 2001).

All things considered, this is a good time to be an astronomer. Overall increases in federal funding and NASA's increased number of space missions have led to a demand for astronomers. The majority of Ph.D. recipients can expect to be employed in their field of study (AIP 1999 Initial Employment Report, http://www.aip.org/statistics/trends/emptrends.htm). According to the AIP Initial Employment Report, 76 percent of recent astronomy Ph.D.s accepted postdoctoral positions, temporary research positions that allow them to perform research and establish themselves in the field. Postdoctoral positions are fairly diverse in nature, ranging from positions in which 100 percent of the individual's time is available for curiosity-driven research to positions in which the postdoc teaches or performs other work for a significant fraction of his or her time. Although postdoctoral positions occasionally convert to permanent positions, this eventuality is rare.

Only a small fraction of the new astronomy Ph.D.s, about 2 percent, reported being unemployed. The remaining 20 percent or so of the respondents accepted some kind of permanent position, either inside or outside of academia. Almost 90 percent of those who earned an astronomy bachelor's degree in 1997–1998—and who responded to the survey—said that they would pursue the same degree again if given the chance.

The median salary for astronomy Ph.D. recipients working in a postdoctoral position at a university was $36,000. The median income for physics Ph.D. recipients was slightly lower in the class of 1997–1998, at $35,000. Potentially permanent positions in academia earned slightly more than the postdoctoral salary levels, with a median income of $38,000. All of these salary levels contrast sharply with the median salary for graduates who take up employment in industrial positions. For the graduating class of 1997–1998, the median income for industrially employed individuals with a Ph.D. was $62,700. Clearly, the tangible and intangible benefits of the academic life come with a pay cut. Bachelor's degree recipients who choose to begin work in industrial jobs also fare well, with a median salary of $40,000, better than their more highly educated colleagues who take academic posts.

It is heartening to note that about two-thirds of the survey respondents felt that their education adequately prepared them for their career. Whether one continues in academia, takes up employment in industry, or moves into an alternative career choice, training in physics and astronomy clearly provides a set of skills that are useful to employers. Furthermore, for astronomy Ph.D. recipients, nearly all respondents felt that their undergraduate education adequately prepared them for graduate study. Although this response may seem obvious, it shows that the astronomy and physics undergraduate departments overall are doing their job.

The National Science Foundation also gathers workforce statistics on many sciences, including astronomy, although it does not provide specific statistics on the astronomical sciences (*Science and Engineering Indicators 2000*). This blending of fields tends to suppress particular trends that are related to astronomers. However, some interesting statistical results can still be found in the report.

One NSF statistic is the median salary for various scientific disciplines. For 1997 (the most recent tabulated data available) physicists and astronomers with a Ph.D. had a median salary of $73,000. Those with M.S. degrees earned $58,000, while those with B.S. degrees made $42,000. The economic benefit of completing a doctorate degree is fairly clear.

The NSF also tabulates the percentage of scientists working in an area closely related to their field. For those physicists/astronomers with a Ph.D., 54.6 percent were employed in an area closely to their field, while only 41.5 percent with an M.S. were thus employed. For those earning only a bachelor's degree, only 29.2 percent were employed in a field related to their degree. These statistics support the data obtained by the AIP, which indicate that the majority of those earning an astronomy doctorate are employed in their field.

Finally, the salary imbalance related to gender seen in other fields of endeavor is duplicated in all fields of science and engineering. Considering all fields and those with doctorate degrees, in the United States, the median salary for a male scientist or engineer was $67,000, while a female scientist or engineer earned a median salary of only $50,000. For physical scientists with doctorate degrees, the median salary levels were $66,900 for men and $54,300 for women. These values were tabulated for 1997. Past years show a similar disparity. Clearly, astronomy and the other sciences are not immune from the influence of wider societal inequalities.

CONCLUSION

Astronomy depends heavily on federal funds, but it is the astronomers who carry out the research that the public has come to enjoy and even expect. Without people to carry out the research and explain it to nonexperts, the mysteries of the universe will be available only to a tiny fraction of the world's population. While only a small number of individuals end up becoming professional astronomers, studying the universe is still expensive. The federal government spends a total of approximately $400 million each year on astronomical research (excludes NASA's spending on major space science initiatives such as the International Space Station and the Space Shuttle Program). This sum will most likely continue to grow as larger, more sensitive telescopes are needed to uncover the mysteries of the universe. Is the knowledge we gain worth the expense? The public seems to think so. On the covers of the nation's magazines, on TV, in newspapers, and in big-screen movies worldwide, astronomy is a very public enterprise. The public enjoys the results of astronomical research and values the investment the federal government makes in it. In a 1998 Gallup opinion poll, 58 percent of those surveyed thought that NASA's space program brought benefits to the nation, although in the same poll, only 21 percent of the respondents thought NASA's budget should be increased. It is unlikely this public appreciation will disappear anytime soon. And as we uncover more information about the universe, answering long-unanswered questions, we find there is still more that we do not understand. For all of our sakes, we hope that there will always be a demand for trained astronomers and a public willing to fund their research.

Chapter Nine

Organizations and Associations

Astronomy has a wide range of devotees, including the general public, active amateurs, and professional astronomers. There are organizations throughout the country and the world that specialize in the needs of each class of astronomy enthusiast. Most professional astronomy organizations were formed in the late nineteenth century, while the majority of the amateur organizations have been formed more recently. Regardless of when they were constituted, organizations play a vital role in the ongoing success of astronomy through the dissemination of data, results, and ideas.

The organizations presented in this chapter promote the progress and enjoyment of astronomy through a number of activities. First and foremost, professional societies publish scientific journals. Journals serve to document and archive scientific results. They allow the dispersal of new knowledge and, before the spread of the Internet, were the primary source of astronomical information to active astronomers. Professional societies also organize most of the meetings at which astronomers gather to share their recent research and to plan new research, new telescopes, and new missions. Education and public outreach also have become major components of professional astronomical meetings in the past 10 years. Specialized professional meetings are often held to share results on specific classes of objects (e.g., planetary nebulae), on specific wavelength regions (e.g., millimeter observations), or even on specific objects. These meetings are sometimes sponsored by professional associations, sometimes by interested individuals at particular universities or research institutes.

Professional astronomy organizations typically have members worldwide. Scientists interact and collaborate internationally for a number of reasons. First, the entire sky cannot be observed from just one geographical location. To see much of the southern sky, for example, telescopes must be located either in space or in the Southern Hemisphere. Second, there is so much specialization within astronomy that sometimes, in order to find collaborators, a given astronomer may need international partners for scientific projects. The diverse experiences and backgrounds that international collaboration can bring to bear on any given problem can be enormously beneficial. International scientific collaboration can also benefit international understanding by bringing citizens from a variety of countries together in the pursuit of common scientific goals. During the cold war, for example, international scientific collaboration in astronomy continued between countries that had significant political differences.

Amateur associations play a vital role, especially in astronomy, where amateurs can provide excellent scientific results with modest instrumentation. However, amateur associations exist mainly to allow individuals to share their interest in astronomy. Typically, scientific results presented at amateur meetings take a back seat to sharing new technical information about a given telescope, the latest pictures of a favorite object, or a summary of the latest late-night observation session. However, the quasi-professional organizations, such as the American Association of Variable Star Observers, do provide high-quality astronomical data and archives that professional astronomers cannot or do not spend their time gathering.

Finally, astronomers are members of a number of associations that may not focus exclusively on astronomy. These organizations broaden the range of topics that astronomers follow and serve to focus the interests, needs, and concerns of scientists generally. In the following sections, we have presented a list as comprehensive as possible of astronomy-related organizations. In the following sections we will highlight a few of the most important organizations (professional and amateur) and provide a reasonably complete list of additional resources to the world's astronomical societies.

PROFESSIONAL ASTRONOMY ORGANIZATIONS

American Astronomical Society (AAS)
2000 Florida Avenue, NW
Suite 400
Washington, DC 20009
United States of America
Telephone: 202-328-2010
Email: aas@aas.org
Web site: http://www.aas.org/

Founded in 1899, the AAS is the second-largest professional astronomical society in the world. The mission of the AAS is to advance understanding of the astronomical sciences. The AAS currently has more than 6,000 members, including approximately 1,000 international members. The AAS is governed by a council, and members of the council serve three-year terms. The society has two meetings per year, in a variety of locations around the United States and Canada. The AAS has five specialized divisions—the Division of Planetary Sciences, the Solar Physics Division, the High Energy Astrophysics Division, the Division on Dynamical Astronomy, and Historical Astronomy Division. The AAS publishes a number of professional publications, including the *Astrophysical Journal, Astrophysical Journal Letters, Astrophysical Journal Supplement*, the *Astronomical Journal*, and the *Bulletin of the American Astronomical Society*. These journals were all founded before the formation of the society, were operated independently for a number of years, and were ultimately acquired by the association to guarantee their longevity. The AAS also publishes a number of internal publications, including a newsletter, a membership directory, several informational brochures, and specialized committee publications. Membership is limited to those who actively work in or support professional astronomy. The AAS offers a number of awards, most available only through a nomination process, each year in addition to several grant programs. The AAS Web site has complete information on the activities of the society, a Job Register, educational information, details of society committee activity, a membership directory, and more.

American Physical Society (APS)
APS Headquarters
One Physics Ellipse
College Park, MD 20740-3844

United States of America
Telephone: 301-209-3200
Web site: http://www.aps.org/

While it does not include *astronomy* in its title, the American Physical Society counts many astronomers as members and has a separate division dedicated to astrophysics. In addition to the astrophysics division, the APS has 13 other divisions covering everything from biophysics to fluid dynamics. The APS has more than 40,000 members. In addition to publishing many of the world's most widely read physics journals, the APS conducts more than 20 national, divisional, and regional meetings each year. The APS has always taken an active role in public policy, and many of the presidential science advisers have been members of the APS. The APS also actively supports physics education and public outreach. Unlike many scientific societies, the APS also monitors the human rights of scientists around the globe and maintains regular communication with policy makers worldwide. In support of the profession, the APS maintains career development and committees on women and minorities in physics. Finally, the APS recognizes professional accomplishment with a large number of prizes and awards as well as a special elected membership class, the APS Fellow.

Astronomical Society of the Pacific (ASP)
390 Ashton Avenue
San Francisco, CA 94112
United States of America
Telephone: 415-869-2914
Web site: http://www.astrosociety.org/

The ASP is the oldest professional astronomical society in the United States. Founded in 1899 by a number of professional astronomers in northern California, the ASP has expanded from being a strictly professional society to being a general society, with both professional and amateur members and services. The society was founded after its early members grouped together to watch a rare solar eclipse. Perhaps because of its origins, the ASP actively seeks to keep professionals and amateurs informed of the latest observational results and techniques. The ASP publishes a professional journal, *Publications of the Astronomical Society of the Pacific*, a news and information magazine, *Mercury*, and a number of internal society communications. The ASP has an annual meeting, held in a variety of locations. Membership is open to anyone. The ASP is particularly active in the area of education and public outreach. It works with science educators to expand the teaching of astronomy in grades K–12. The society also organizes public lectures and activities such as travel tours to view astronomical events such as eclipses. Finally, the ASP publishes a conference proceedings series, designed to rapidly distribute the content of specialized scientific meetings to the wider astronomical community.

Canadian Astronomical Society
Society Business Office
Department of Physics
Queens University
Kingston, ON K7L 3N6
Canada
Telephone: 613 533 6000 ext. 74431
Web site: http://www.casca.ca/

The Canadian Astronomical Society (CASCA), formed in 1971 and incorporated in 1983, has about 400 members and sponsors an annual scientific meeting. The society is devoted to the promotion and advancement of knowledge of the universe through research and education. CASCA publishes a newsletter twice per year (on the equinoxes). It also makes a number of awards and maintains an up-to-date Web site with news, membership information, and a list of jobs in astronomy. Membership is not limited to residents of Canada and costs $60 (Canadian) per year for ordinary members, $25 (Canadian) for student membership.

International Astronomical Union (IAU)
IAU-UAI Secretariat
98bis, Bd. Arago
F-75014 Paris
France
Telephone: +33 1 4325 8358
Email: iau@iap.fr
Web site: http://www.iau.org/

The IAU serves as the international association for astronomy and is the largest professional astronomical society in the world. The IAU is similar to other international scientific unions, such as the Geophysical Union or the Physical Union, and organizes a scientific meeting every three years. These meetings, called General Assemblies, host a number of specialized conferences, usually topical in nature, in addition to sessions based around a number of divisions and commissions. The IAU also sponsors Working Groups to address technical issues such as the naming of newly discovered celestial objects. The

IAU helps astronomers in developing countries in a number of ways including organizing visits from astronomers in more developed countries and sponsoring meetings on a variety of topics worldwide. It also provides grants for astronomers to attend the General Assembly and other conferences. The IAU publishes an Information Bulletin and a membership directory. Proceedings of the various IAU meetings (General Assemblies, Symposia, and Colloquia) are published by a third-party publisher. The IAU also publishes a book titled *Highlights of Astronomy* in conjunction with the General Assembly every three years. This book serves as an authoritative record of new results in the field. Membership is obtained through nomination, which is approved by each nation's national committee. The current membership is about 10,000, with representation from most of the world's nations. The IAU maintains a telegram service to distribute breaking news around the world, such as supernova and comet discoveries. The IAU is the organization responsible for naming of astronomical objects and standardization of nomenclature, an enormous task in an age of multiple, high-resolution telescopes operating around the clock. The IAU awards the Peter Gruber Cosmology Prize and Astronomy Fellowships of the Peter Gruber Foundation. The Cosmology Prize, established in 2000, annually awards U.S. $150,000 to scientists of any nationality working in the fields of astronomy, physics, mathematics, and philosophy of science for scientific advances in our understanding of the universe and how we perceive it. The fellowships, two awarded every three years, are for extremely promising astrophysicists to fund a year of research and travel as postdoctoral scholars.

OTHER ASTRONOMICAL GROUPS AND ASSOCIATIONS

There are too many amateur associations to include in this small volume, so we include here a sampling of astronomical societies around the world. There is a more complete listing of amateur astronomy associations available on the Internet at AstroWeb (http://www.stsci.edu/science/net-resources.html), a consortium of seven astronomical institutions that have agreed to provide online astronomy-related resources and information since early 1994.

American Association of Variable Star Observers (AAVSO)
25 Birch Street
Cambridge, MA 02138
United States of America

Telephone: 617-354-0484
Web site: http://www.aavso.org/

The American Association of Variable Star Observers (AAVSO) is a nonprofit worldwide scientific and educational organization of amateur and professional astronomers who are interested in stars that change in brightness, so-called variable stars. Founded in 1911 at Harvard College Observatory, the AAVSO was initially established to coordinate amateur variable star observations. The AAVSO is now international in scope with members in more than 40 countries and the largest association of variable star observers worldwide. Membership in the AAVSO is open to anyone interested in variable stars or in contributing to the support of valuable research. By coordinating the observational efforts of interested amateurs, the AAVSO serves a valuable role providing abundant data on a class of objects that professional astronomers often ignore. The AAVSO publishes a journal, *The Journal of the AAVSO*, which features scientific papers that focus on variable stars in addition to sponsoring two meetings per year. At the meetings, members present their latest work, and occasionally professional astronomers hold workshops on observational techniques or detailed analysis procedures.

The Astronomical League
Address varies with elected leadership.
Webs site: http://www.astroleague.org/

The Astronomical League is the largest federation of amateur astronomy societies in the world. The League exists to promote the science of astronomy by fostering astronomical education, by providing incentives for amateur astronomical observation and research, and by assisting communication among amateur astronomical societies. The league publishes a quarterly newsletter, *The Reflector*, which keeps members informed of amateur activities all over the country. The league also offers a number of observation-based awards for a variety of accomplishments.

International Dark-Sky Association (IDA)
3225 North First Avenue
Tucson, AZ 85719-2103
United States of America
Telephone: 520-293-3198
Fax: 520-293-3192
Email: ida@darksky.org
Web site: http://www.darksky.org/ida/index.htm/

Incorporated in 1988, the International Dark-Sky Association strives to be effective in stopping the adverse environmental impact of lighting on dark skies by building awareness of the problem of light pollution. IDA's publications propose realistic solutions to light pollution and provide material to educate people everywhere about the value and effectiveness of quality nighttime lighting. The IDA believes that dark skies can be preserved and the nighttime environment can be improved through improved outdoor lighting. The IDA currently has about 6,000 members worldwide. IDA is also active in building awareness of the adverse problems affecting astronomy from radio frequency interference (RFI), space debris, and other environmental impacts that have the potential to reduce or eliminate our ability to view the universe in which we live. IDA focuses on education by producing a regular newsletter, information sheets, brochures, leaflets, economic information, examples of good lighting design, and other resources. The IDA also gives out Good Lighting Awards and maintains active media contacts.

The Planetary Society
65 North Catalina Avenue
Pasadena, CA 91106-2301
United States of America
Telephone: 626-793-5100
Web site: http://www.planetary.org/

Founded in 1980 by Carl Sagan, Bruce Murray, and Louis Friedman, the Planetary society seeks to encourage the exploration of our solar system and the search for extraterrestrial life. The Society supports the very popular *seti@home* project, a distributed computing project to use the computers of millions of people worldwide to search for possible signals from extraterrestrial life. The society has more than 100,000 members worldwide and is the largest space-related society. Membership is open to all people interested in their mission of enhancing space exploration opportunities. The Planetary Society encourages all space-faring nations to explore other worlds, provides public information, and supports educational activities about the exploration of the solar system and the search for extraterrestrial life. It supports and funds innovative and novel research and development projects that can seed future projects of planetary exploration and seeks ways to involve as many people as possible in the excitement of space exploration.

A SELECTION OF ASTRONOMICAL ASSOCIATIONS WITH USEFUL WEB LINKS

The following is a partial list of astronomical associations compiled by the AstroWeb (http://www.stsci.edu/science/net-resources. html).

Agrupación Astronómica de Madrid (AAM). http://www.iac.es/AA/AAM/ing.html

Amateurs Astronomes du Luxembourg (AAL). http://www.aal.lu/

American Association for the Advancement of Science (AAAS). http://www.aaas.org/

American Association of Amateur Astronomers (AAAA). http://www.corvus.com/

American Geophysical Union (AGU). http://earth.agu.org/

American Institute of Physics (AIP). http://www.aip.org/

American Mathematical Society (AMS). http://e-math.ams.org/

American Meteor Society (AMS). http://www.amsmeteors.org/

Asociación Colombiana de Estudios Astronómicos (ACDA). http://www.geocities.com/acda_colombia

Asociación de Aficionados a la Astronomía—Uruguay (AAA). http://www.internet.com.uy/aaa/

Association Française d'Astronomie (AFA). http://www.cieletespace.fr/

Association of Lunar & Planetary Observers (ALPO). http://www.lpl.arizona.edu/alpo

The Astronomer. http:www.theastonomer.org/index.html/

Astronomical Society of Australia (ASA). http://www.atnf.csiro.au/asa_www/asa.html

Astronomical Society of India (ASI). http://www.rri.res.in/asi/

Astronomical Society of MALTA. http://www.geocities.com/maltastro/

Astronomische Gesellschaft (The German Astronomical Society). http://www.astro.uni-jena.de/Astron_Ges/ag0homee.html

Chinese Astronomical Society (CAS). http://www.bao.ac.cn/cas/

Czech Astronomical Society. http://www.astro.cz/home-e.htm

Denmark Astronomical Society. http://www.dsri.dk/as-uk.html

Euro-Asian Astronomical Society (EAAS). http://www.issp.ac.ru/astro/eaas/index.html

European Astronomical Society (EAS). http://www.iap.fr/eas/

Federation of Astronomical and Geophysical Data Analysis Services (FAGS). http://www.kms.dk/fags/

Hellenic Astronomical Society (HEL.A.S.). http://www.astro.auth.gr/elaset/

Institut National des Sciences de l'Univers/CNRS (INSU). http://www.insu.cnrs-dir.fr/

International Meteor Organization (IMO). http://www.imo.net/

Irish Astronomical Society (IAS). http://www.esatclear.ie/~ias/

Jordanian Astronomical Society (JAS). http://www.jas.org.jo/

Lebanese Amateur Astronomical Society. http://geocities.com/capecanaveral/hall/6865/

Liverpool Astronomical Society. http://www.liv.ac.uk/~ggastro/home.html

National Academy of Sciences—Board on Physics and Astronomy (National Research Council). http://www.nas.edu/bpa/

Royal Astronomical Society (RAS). http://www.ras.org.uk/

Royal Astronomical Society of Canada (RASC). http://www.rasc.ca/

SETI League. http://seti1.setileague.org/homepg.html

SPIE—The International Society for Optical Engineering. http://www.spie.org/

Sociedade Astronomica Brasileira (SAB). http://www.iagusp.usp.br/sab

Sociedad Española de Astronomía (SEA). http://sea.am.ub.es/SEAf_I.html

Société Royale Belge d'Astronomie, de Météorologie et de Physique du Globe (SRBA). http://www.oma.be/BIRA-IASB/SRBA/

Society for Popular Astronomy (SPA). http://www.popastro.com/ (The SPA publishes the quarterly magazine *Popular Astronomy*.)

Southern Astronomical Society Home Page. http://www.sas.org.au/

Students for the Exploration and Development of Space (SEDS). http://seds.lpl.arizona.edu/

Visual Satellite Observers. http://www2.satellite.eu.org/sat/vsohp/

Chapter Ten

Journals, Magazines, and Internet Resources

The print and electronic resources briefly described in this chapter range from professional journals to popular magazines to a few Internet-based resources. A recent search of the Internet with the keyword *astronomy* resulted in over 1 million hits, so the small number of Internet resources listed in this chapter is clearly the tip of the iceberg. If there are specific topics that you need to explore on the Internet, then you should use your favorite search engine and type in the appropriate keywords. In addition, many of the magazines described in this chapter have well-constructed Web sites that have astronomy resource lists of their own (see, for example, http://www.astronomy.com/home.asp, the Web site of *Astronomy* magazine). (For the associated Web sites for all the listed journals, as well as for many others, see the University of Maine Astronomy Journal Summary Internet site at http://www.library.umaine.edu/sec/curtis/info4au/default.htm.) There are also a large number of teaching resources available on the Internet and also available directly from various government agencies.

A word of caution: The Internet is a free publishing environment. Be informed and critical when reading astronomy-related information on the Internet, especially material that is not located at a familiar site.

The resources in the chapter are listed alphabetically. Because of the large number available, this chapter includes almost exclusively astronomy-related journals, magazines, and Internet sites rather than general-science resources, which may touch on astronomy. For a supplementary listing of resources that includes general science, see chapter

10 in David Newton's *Recent Issues and Advances in Physics* (Oryx, 2000).

Annual Reviews of Astronomy and Astrophysics and *Annual Reviews of Earth and Planetary Science*

These publications are 2 of 29 published in a variety of scientific disciplines by Annual Reviews. The blue hardcover volumes are carried by many libraries and provide a comprehensive overview of the most important developments in the respective fields in the past year. Articles in this volume are widely cited by professional astronomers.

Annual Reviews
4139 El Camino Way
P.O. Box 10139
Palo Alto, CA 94303-0139
United States of America
Telephone: 800-523-8635
Fax: 650-424-0910
Email: service@annualreviews.org

The Astronomical Journal

Published by the University of Chicago Press, *The Astronomical Journal* (founded 1849) is one of the world's most respected astronomy journals. This professional journal covers all areas of astronomy, including cosmology, quasars, galaxies, supernovae, variable stars, binary stars, and studies of the solar system. *The Astronomical Journal* has tended to emphasize observational (as opposed to theoretical) papers.

Paul Hodge, Editor
Astronomical Journal
Department of Astronomy
Box 351580
University of Washington
Seattle, WA 98195-1580
United States of America
Telephone: 206-685-2150
Fax: 206-685-0403
Email: astroj@astro.washington.edu

Astronomy

Astronomy is a monthly publication containing sky guides, observing tips, book reviews, equipment reviews, news items, and longer review articles on recent developments in astronomy. The magazine maintains an impressive Web site with a host of additional resources.

Astronomy
21027 Crossroads Circle
P.O. Box 1612
Waukesha, WI 53187-1612
United States of America
Telephone: 800-446-5489
Fax: 262-796-1615
Email: CustomerService@astronomy.com

Astronomy and Astrophysics

Astronomy and Astrophysics, the premier European research journal in the field, has been published since 1969.

Springer-Verlag Heidelberg
Tiergartenstrasse 17
D-69121 Heidelberg
Germany
Telephone: 49-6221-487-635
Fax: 49-6221-487-688
Email: p.meyer@springer.de

The Astrophysical Journal and *The Astrophysical Journal Letters*

Over 100 years old, *The Astrophysical Journal* is a widely respected research publication that covers recent developments, theories, and discoveries. Videos containing animated sequences sometimes complement specific issues. Several of the most important discoveries of the twentieth century were reported first in *The Astrophysical Journal*, including Hubble and Humason's famous 1931 paper on the distance-velocity relationship that has become known as the Hubble law.

Robert C. Kennicutt, Jr., Editor in Chief
The Astrophysical Journal
Steward Observatory
University of Arizona
933 North Cherry Avenue
Tucson, AZ 85719-0065
United States of America
Telephone: 520-621-5145
Fax: 520-621-5153
Email: apj@as.arizona.edu

A. Dalgarno, Letters Editor
Astrophysical Journal
Center for Astrophysics—Mail Stop 14
30 Garden Street
Cambridge, MA 02138
Telephone: 617-495-4479
Fax: 617-495-8317
Email: apjl@cfa.harvard.edu

AstroWeb

AstroWeb, a listing of resources freely available on the Internet, contains its own search engine. The site includes resources listed under the following broad categories: Observing Resources; Data Resources; Publication-related Resources, People-related Resources, Organizations, Software Resources, Research areas of Astronomy, Lists of Astronomy Resources, and Astronomical Imagery. Especially helpful are the mirror sites, which are updated daily, while dead links are removed regularly.

Web site: http://www.stsci.edu/astroweb/astronomy.html

Astrophysics Data System, (ADS) Astronomy and Astrophysics Abstract Service

The ADS Abstract Service allows astronomers to perform sophisticated searches for astronomical articles. The searches can be based on author, date, title, keywords, abstract words, source names, or any combination of these and other elements. The search results then allow researchers to read or download the appropriate articles. Most journals require that your institution subscribe to the journal in question to access recent publications.

Web site: http://adsabs.harvard.edu/ads abstracts.html

Bulletin of the American Astronomical Society (BAAS)

BAAS is most familiar to astronomers as the publication that accompanies meetings of the American Astronomical Society, held twice annually. *BAAS* contains abstracts of talks, poster presentations, and special sessions. *BAAS* also publishes the annual reports of American university astronomy departments.

Robert W. Milkey, Editor
American Astronomical Society
2000 Florida Avenue, NW #400
Washington, DC 20009
United States of America
Telephone: 202-328-2010
Fax: 202-234-2560
Email: milkey@aas.org

Icarus

Icarus is the official journal of the Division of Planetary Sciences (DPS) of the American Astronomical Society and publishes research in solar system studies. Recent discoveries of extrasolar planetary systems mean that *Icarus* now publishes papers discussing not only our solar system, but others as well.

***Icarus* Editorial Office**
413 Space Sciences Building
Cornell University
Ithaca, NY 14853-6801
United States of America
Telephone: 607-255-4875
Fax: 607-255-6354
Email: icarus@astrosun.tn.cornell.edu

International Astronomical Union (IAU) Symposia

The International Astronomical Union publishes proceedings of its meetings in the Symposia series. The IAU is described in the previous chapter.

ASP Conference Proceedings Series/IAU Publications
Room 211—KMB
Brigham Young University
Provo UT 84602
United States of America
Telephone: 801-378-2111
Fax: 801-378-4049
Email: pasp@byu.edu

International Comet Quarterly (ICQ)

ICQ is devoted exclusively to the study of comets. Unlike most professional journals, it serves both amateur and professional astronomy communities.

International Comet Quarterly
Mail Stop 18
Smithsonian Astrophysical Observatory
60 Garden Street
Cambridge, MA 02138
United States of America
Email: icq@cfa.harvard.edu

Journal for the History of Astronomy

The *Journal for the History of Astronomy* presents current research on the history of astronomy since ancient times. Some articles discuss the historical links among astronomy, mathematics, and physics.

Michael Hoskin, Editor
Journal for the History of Astronomy
Churchill College
Cambridge
England CB3 0DS
Telephone: 01223-840284
Fax: 01223-565532
Email: mah15@cus.cam.ac.uk m

Journal of Geophysical Research (JGR)

The *Journal of Geophysical Research* is published by the American Geophysical Union (AGU), which has editorial responsibility for a large number of journals published monthly, including the following of particular interest to astronomy:

JGR—Atmospheres
JGR—Oceans
JGR—Planets
JGR—Space Physics
Radio Science

American Geophysical Union
2000 Florida Avenue, NW
Washington, DC 20009
United States of America
Telephone: 800-966-2481
Fax: 202-328-0566

Kluwer Academic Publishers (KAP)

KAP publishes a number of astronomy-related scientific journals for professionals, including the following:

Celestial Mechanics & Dynamical Astronomy
Earth, Moon, and Planets: An International Journal of Solar System Science
Experimental Astronomy: An International Journal on Astronomical Instrumentation and Data Analysis
Solar Physics
Space Science Reviews

Kluwer Academic Publishers
Van Godewijckstraat 30
P.O. Box 17
3300 AA Dordrecht
The Netherlands
Telephone: +31 78 639 23 92
Fax: +31 78 639 22 54

Mercury

Mercury is a bimonthly magazine published by the Astronomical Society of the Pacific (ASP). It includes brief (one-page) columns as well as longer articles about recent astronomical discoveries, turning points in astronomical history, and astronomical education.

The Astronomical Society of the Pacific
390 Ashton Avenue
San Francisco, CA 94112
United States of America
Telephone: 415-337-1100
Fax: 415-337-5205
Email: editor@aspsky.org

Meteoritics and Planetary Science (MAPS)

A publication of the Meteoritical Society, *MAPS* publishes invited reviews, research articles, editorials, and book reviews, all related to planetary science. The journal strives to serve professional scientists from diverse backgrounds, including astronomy, chemistry, geology, physics, and biology.

Derek Sears, Editor
Meteoritics and Planetary Science
Chemistry Building
University of Arkansas
Fayetteville, AR 72701
United States of America
Telephone: 501-575-7625
Fax: 501-575-7778
Email: meteor@uark.edu

Monthly Notices of the Royal Astronomical Society

This highly respected journal is a publication of the Royal Astronomical Society and is one of the leading primary research journals in astronomy and astrophysics.

Royal Astronomical Society
Burlington House
Piccadilly
London W1V 0NL
United Kingdom
Telephone: +44 171 734 3307/4582
Fax: +44 171 494 0166

Nature

The journal *Nature* often publishes important, breaking, and newsmaking astronomical results. It maintains editorial offices in seven cities around the world and publishes a number of specialized journals. Astronomy results appear in the main journal, *Nature*.

Nature
Porters South
4 Crinan Street
London N1 9XW
United Kingdom

Telephone: +44 (0)20 7833 4000
Fax: +44 (0)20 7843 4596/7
Email: nature@nature.com

New Astronomy

Although most astronomy journals require electronic submission and publish results electronically simultaneously with print editions, *New Astronomy* is the first fully electronic astronomical journal. It covers all areas of astronomy and astrophysics.

Carl Schwarz, Publisher
New Astronomy
P.O. Box 103
1000 AC Amsterdam
The Netherlands
Telephone: +31 20 485 2355
Fax: +31 20 485 2580
Email: c.schwarz@elsevier.nl

The Planetarian

The Planetarian publishes information of interest to the planetarium community. The journal does include book reviews of some general interest, but it is devoted primarily to articles that pertain to technical issues, planetarium management, and the design of planetarium shows.

John Mosley, Executive Editor
The Planetarian
Griffith Observatory
2800 East Observatory Road
Los Angeles, CA 90027
United States of America
Telephone: 323-664-1181
Fax: 323-663-4323
Email: jmosley@GriffithObs.org

Planetary and Space Science

This interdisciplinary journal is the official publication of the Planetary and Solar System Sciences Section of the European Geophysical Society. Among the areas discussed in this journal are cosmic chemistry, terrestrial planets and satellites, planetary atmospheres, and exobiology.

European Geophysical Society (EGS) Office
Max-Planck-Str. 13
37191 Katlenburg-Lindau
Germany
Telephone: +49-5556-1440
Fax: +49-5556-4709
Email: egs@copernicus.org

Publications of the Astronomical Society of the Pacific (PASP)

The *PASP* has been published since 1889. *PASP* publishes scientific astronomical results as well as instrumentation papers, invited reviews, and dissertation summaries.

Anne P. Cowley, Co-Editor
Department of Physics and Astronomy
Arizona State University
Box 871504
Tempe, AZ 85287-1504
United States of America
Telephone: 480-965-6062
Fax: 480-965-8011
Email: pasp@asu.edu

Revista Mexicana de Astronomía y Astrofísica

Revista Mexicana de Astronomía y Astrofísica has published original research papers in all branches of astronomy, astrophysics, and closely related fields since 1974. Two volumes are issued annually. Papers are published in English, with an abstract in Spanish.

Instituto de Astronomía
Universidad Nacíonal Autónoma de México
Apartado Postal 70-264
Mexico 04510, D.F., Mexico
Email: rmaa@astroscu.unam.mx

Sky and Telescope

Sky and Telescope is a monthly magazine intended for a popular readership. Like *Astronomy*, it has regular monthly columns, book reviews,

reviews of telescopes and instrumentation, news items, and longer articles. It also includes several observing-related columns and a monthly observing guide.

Sky Publishing Corporation
49 Bay State Road.
Cambridge, MA 02138
United States of America
Telephone: 800-253-0245
Fax: 617-864-6117
Email: For full listing, see http://www.skypub.com/spc/contact/email.html

SkyView Virtual Observatory

This excellent resource provides a data archive of raw astronomical data (images). The interface allows the user to specify the position and the field of view and then generates an image at the specified wavelength(s), drawing from its archive, which covers the spectrum from radio waves to gamma rays. The complexity of the interface can be set by the user and varies between nonastronomer and advanced.

Web site: http://skyview.gsfc.nasa.gov/

SpaceKids

Maintained by space.com, this graphics-intensive site contains an enormous amount of information for children interested in astronomy. Included are images, movie sequences, news updates, information on upcoming missions, an ask-an-astronomer site, and games.

Web site: http://www.spacekids.com/

For a more complete listing of astronomy-related journals, use the following link to connect to the University of Maine library: http://www.library.umaine.edu/sec/curtis/info4au/default.htm

Glossary

active galaxy A galaxy that exhibits excess emission of radiation for its type.

active optics Optical components that can be slowly distorted to compensate for deformations due to gravity and other effects.

adaptive optics Optical components that can be distorted in real time to compensate for the image-distorting effects of the atmosphere.

angular resolution A measure of the smallest detail that an imaging system can produce for objects at a given distance. Angular resolution of most Earth-bound telescopes is limited by **seeing**.

anthropic principle The assumption that if the universe were not constructed in the way it appears to be (in terms of fundamental physical properties), life would not have originated, and we would not be here to observe it.

aperture synthesis A technique involving the combination of light from multiple telescopes on a rotating Earth that uses Fourier transforms to make images from the detected two-dimensional interference pattern.

archaeoastronomy The study of what ancient civilizations knew about the sky and how they identified with the objects in the sky. This field includes both the study of ancient sites as well as cultural studies of civilizations past and present.

astrobiology The study of the origin and evolution of life, including how the building blocks of life came together on the early Earth and in other possible locations in the universe.

astrometry The precise measurement of the relative location on the sky of celestial objects.

astronomical unit (AU) The mean distance between the earth and the sun (1.5×10^{11} m)

Big Bang A term used to describe the origin of an expanding universe. The **cosmic microwave background (CMB)** radiation is the residual signature of this energetic event.

Big Crunch A hypothesized end to our universe if the expansion we currently observe were to slow down and reverse—a scenario thought unlikely to occur, as recent evidence shows the expansion of our universe is accelerating.

black hole A region of the universe so dense that the escape velocity exceeds the speed of light. Thus, black holes have gravitational fields so strong that not even light can escape from their "surface." Black holes can be formed at the end of a massive star's life through a supernova explosion or formed in the cores of galaxies through the coalescence of extreme quantities of matter or other black holes.

bolometer A device sensitive to electromagnetic radiation, which changes the electrical resistance of the device when light is absorbed by its surface. Can be used for imaging.

CCD (charge-coupled device) A solid-state electronic device used to gather light. CCDs are composed of a grid of photon-absorbing material and electronics that collect and measure the electrons released by the material when light hits it. Used in astronomical imaging and **spectroscopy**.

closed universe One possible geometry of our three-dimensional universe in which there is more matter than necessary to gravitationally counteract the expansion we observe. Such a universe would end in a **Big Crunch**.

computational astrophysics A specialized area of research that uses computers and numerical modeling to simulate astrophysical situations. This discipline has grown dramatically with the advent of powerful, inexpensive computers and allows astronomers to study system evolution over millions or billions of years.

coronal mass ejections The ejection into space of highly energetic particles due to sudden magnetic field changes in the outermost regions of the sun's atmosphere.

cosmic microwave background (CMB) Light received from all directions in the sky that peaks in intensity at a wavelength of a few millimeters. Seen as important evidence of a **Big Bang** origin to the universe.

cosmological constant A parameter in Einstein's theory of relativity that measures the energy content of space itself. In later life, Einstein declared that the inclusion of the constant was one of his biggest mistakes, but recent evidence suggests that there likely is "dark energy" in space itself, causing the acceleration of the expansion of the universe.

cosmology The study of the universe, including its origin and evolution.

dark matter A constituent of the matter in the universe known to exist only through its gravitational influence on other matter, estimated to make up to 90 percent of the mass of the universe.

distance ladder A series of observational techniques allowing astronomers to measure astronomical distances from nearby objects to the most distant ones.

Doppler shift A shift in the detected frequency of a wave due to the motion of either the source or the observer. In astronomy, objects in motion away from the Earth exhibit a redshift, and objects in motion toward the Earth exhibit a blueshift.

electromagnetic spectrum The complete set of wavelengths (or frequencies) of propagating energy in the form of coupled periodic waves of electric and magnetic fields. The spectrum ranges from long radio waves to short-wavelength gamma rays.

exobiology The study of the biology of life beyond Earth.

extrasolar planet A planet that is not a part of the solar system, usually orbiting another star, although potential planets not associated with a host star would also be considered extrasolar planets.

flat universe One possible geometry of our three-dimensional universe in which there is just enough matter to gravitationally counteract the expansion we observe.

Fourier transform A mathematical transformation involving trigonometric functions. Typically used to transform from a frequency domain to a spatial domain and vice versa. Used frequently in interferometry because the interference pattern detected by an interferometer is the Fourier transform of the image.

gamma ray burster An object that emits enormous bursts of high-energy gamma rays. Thought to be the result of merging neutron stars.

gravitational lens When a massive object lies between an observer and a bright distant object, the rays of light from the distant object are bent by the mass of the nearby object. This is one of the predictions of Einstein's general theory of relativity that has been widely confirmed.

helioseismology The study of the pulsation modes of the sun. By studying these modes, information about the structure of the interior of the sun can be determined.

interferometry A general observational technique that makes use of the interference properties of light. By combining light received from spatially separated instruments and studying the resulting interference pattern, spatial detail about the emitting source can be obtained. The Very Large Array (VLA), with its multiple radio-telescope dishes, is an interferometer.

intergalactic medium (IGM) The material found in space between galaxies.

interstellar medium (ISM) The material found in space between stars, including neutral hydrogen, molecular clouds, and ionized gas. *Also see* **intergalactic medium IGM**.

Kuiper Belt A thick disk of sparse icy material in the plane of the solar system beginning beyond the orbit of Neptune and extending to about 1,000 AU. The Kuiper Belt is the location from which short-period comets arise and was originally identified in 1951 by Gerard Kuiper, a well-known planetary scientist.

laser An acronym derived from a radiative process—light amplification by stimulated emission of radiation. When atoms or molecules exist with an inverted energy level population and background light passes through the region, the light can be amplified through the stimulated emission of radiation.

light pollution Light that is not directed where it is of use. Light pollution stems from poorly designed lighting fixtures and inappropriate design of outdoor lighting systems. Among other things, it interferes with astronomical observation.

neutrino A fundamental subatomic particle produced in many nuclear reactions. Neutrinos are thought to have a very small mass, are electrically neutral, and do not readily interact with normal matter.

Oort Cloud The outermost region of the solar system, which hosts icy bodies that represent the residue left after the formation of the solar system and is the origin of the long-period comets. The Oort Cloud ranges from the outer regions of the **Kuiper Belt** to halfway to the nearest star.

open universe The most likely geometry of our three-dimensional universe, in which there is not enough matter to counteract the expansion we observe and the possible accelerative force of the **cosmological constant**.

protoplanet A planet that is in the early stages of its formation.

pulsar A radio star with pulsating brightness discovered by Jocelyn Bell and Anthony Hewish in 1967. Pulsars are now known to be rotating neutron stars that emit bursts of radio emission in a regular, repeating pattern.

quasar Quasars (quasi-stellar radio sources) are located at great distances and consequently have very large measured **redshift**. They are among the most distant objects that we can see in the universe.

radio telescope A type of telescope designed to collect and focus light with wavelengths from about 1 m to a fraction of a millimeter.

redshift The measure of the velocity of recession of an object, determined through the measurement of the change in wavelength of light emitted by the moving source due to the Doppler effect.

Schwarzschild radius The radius of a region surrounding a black hole from which radiation cannot escape. This radius depends only on the mass of the black hole, and a simple rule of thumb is that $R = 3 \times M$, where R is the Schwarzschild radius in kilometers, and M is the mass of the black hole in solar masses.

seeing A measure of the current atmospheric-limited resolution of a telescope at a particular location. Seeing can be measured by observing the apparent size in arcseconds of single stars seen through telescopic systems.

sensitivity A measure of the detection threshold of instrumentation. More sensitive instruments can detect weaker signals.

singularity A point of finite mass and zero volume; the "center" of a **black hole**.

speckle interferometry An observational technique of acquiring a large number of short-exposure images and then combining the images to eliminate the image-distorting effects of the atmosphere.

spectral lines The light emitted or absorbed by atoms and molecules when they transition from one energy state to another. Spectral lines can inform astronomers about the physical state of the gas where the lines originated.

spectral resolution The measure of the smallest distinguishable frequency or wavelength unit provided by a spectroscopic system.

spectrograph An instrument that disperses light so that different wavelengths can be studied separately.

spectroscopy A general term describing the study of the dispersed light.

standard candle A term for a class of object that has a known brightness and therefore may be used to measure distance by the inverse-square law. Cepheid variable stars are standard candles because they have a known brightness based on the period of their brightness fluctuations.

star hopping A technique of pointing a telescope at a bright, well known star, then moving to a nearby, less well known star and repeating as necessary until the telescope is pointed in the direction of the desired object. Usually used by amateurs who do not wish to employ coordinate systems to find celestial objects.

sunspot A region on the sun that is cooler than the surrounding region due to the interaction of magnetic fields with the hot material near the surface of the star.

supernova A stellar explosion that takes place when the nuclear fusion reactions at the core of a star can no longer support the mass of the overlying layers of stellar material. A collapse of the stellar material begins, quickly accelerates, then rebounds explosively off the dense core of the star formed during the collapse. The result is a spectacular release of energy and the production of many heavy elements. Supernovae release so much light that they can be detected from the farthest reaches of the universe. The remains of supernovae are either neutron stars or **black holes**.

telescope A device to collect electromagnetic radiation from celestial objects. Telescopes take a variety of forms based on the wavelength of light they are designed to gather.

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About the Authors

CHRISTOPHER G. DE PREE is director of the Bradley Observatory and an assistant professor of physics and astronomy at Agnes Scott College in Atlanta, Georgia. De Pree studies massive star formation in the Milky Way Galaxy, and uses radio telescopes to image regions of space that are so deeply embedded in dense clouds that they are undetectable with optical telescopes.

KEVIN MARVEL is currently serving as the associate executive officer for policy programs with the American Astronomical Society. In his current position, he lobbies Congress and the administration for increased funding for basic research and directs the AAS career services program.

ALAN AXELROD created The Ian Samuel Group, Inc., and now serves as its president. He is the author of numerous books, including the *Dictionary of American Folklore, The Macmillan Dictionary of Military Biography*, and *Dictators and Tyrants.*