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Exploring the Milky Way

Course Guidebook

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David M. Meyer is a Professor of Physics and Astronomy in the Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) at Northwestern University. He earned his BS in Astrophysics at the University of Wisconsin–Madison after completing a senior honors thesis on ultraviolet interstellar extinction with Professor Blair Savage. He earned his MA and PhD in Astronomy at the University of California, Los Angeles, working with Professor Michael Jura on measurements of the cosmic microwave background radiation from observations of interstellar cyanogen. He then continued his studies as a Robert R. McCormick postdoctoral fellow at the University of Chicago's Enrico Fermi Institute before joining the Northwestern faculty. During his career at Northwestern, Professor Meyer has served as the chair of the Department of Physics and Astronomy, the director of the Dearborn Observatory, and a founding codirector of CIERA.

Professor Meyer's research focuses on the application of sensitive spectroscopic techniques to astrophysical problems involving interstellar and extragalactic gas clouds. Utilizing a variety of ground- and space-based telescopes, he studies the optical and ultraviolet spectra of stars and quasars to better understand the composition, structure, and physical conditions of intervening clouds in the Milky Way and other galaxies. Over the past 30 years, much of his research has involved space telescopes in general and the Hubble Space Telescope in particular. During this time, Professor Meyer and his collaborators have been awarded $2.3 million in NASA research funding to carry out space observations that have resulted in 33 peer-reviewed publications on topics ranging from the abundance of interstellar oxygen to the gaseous character of distant galaxies. He has also served 6 times on the committee that annually selects the most deserving proposals for Hubble observation time.

As an educator at Northwestern, Professor Meyer has specialized in designing and teaching introductory undergraduate courses in astronomy, cosmology, and astrobiology for nonscience majors. A hallmark of his lectures is the use of Hubble images to bring the latest research into the introductory classroom. His success in such efforts has led to a number of teaching awards, including Northwestern's highest teaching honor, the Charles Deering McCormick Professorship of Teaching Excellence. His other honors include the Martin J. and Patricia Koldyke Outstanding Teaching Professorship, the Weinberg College Distinguished Teaching Award, and the Northwestern University Alumni Excellence in Teaching Award.

Professor Meyer's other Great Courses are *Experiencing Hubble: Understanding the Greatest Images of the Universe* and *A Visual Guide to the Universe*.

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EXPERIENCING HUBBLE
Exploring the Milky Way

Among the many wonders of the night sky, our eyes are drawn to a diffuse band of light stretching from horizon to horizon. This Milky Way glows with the light of billions of stars amid vast clouds of interstellar gas and stardust. It is a vast machine whose spiral structure helps drive the formation of new stars in these clouds and sweeps the matter lost from dying stars into new star-forming clouds. These stars and clouds form the disk-shaped backbone of the large spiral galaxy that is our home.

Among the telescopes studying the Milky Way, none has provided a sharper optical view of its stars, star clusters, and nebulae than the Hubble Space Telescope. The key to its image sharpness is its location in near-Earth orbit, well above the blurring effects of atmospheric turbulence.

This introductory course focuses on exploring and understanding our Milky Way Galaxy through the most remarkable Hubble images of its stars, star clusters, nebulae, and galactic environment. Each of the 12 lectures is centered on a specific image from Hubble's third decade whose individual scientific story ties into a better understanding of the galaxy as a whole. The course is designed to visualize the Milky Way as Hubble sees it and interpret the images in terms of the latest science. Each of the individual lectures is supported and enhanced by additional Hubble images and those taken by a variety of ground-based and space-based observatories. As the course progresses, these stories are woven together to examine the structure, evolution, and eventual fate of the Milky Way.

The Great Course *Experiencing Hubble: Understanding the Greatest Images of the Universe* can be enjoyed before or after this course. A key focus of that course is on understanding the design, history, and operation of the telescope itself, together with the 10 most spectacular images from its first 2 decades of observations.

The course begins by establishing that the Milky Way is one spiral galaxy among hundreds of billions of galaxies in the universe. Hubble's sharp eye is used to detail the characteristics of other spiral galaxies in search of one that best matches our inside view of the Milky Way.

Then, the course presents a Hubble image of a recent comet displayed against an incredibly sharp, deep background of faint stars and galaxies stretching beyond a billion light-years. This image is discussed in the broader context of both the comet's story and the distance scale within and beyond the solar system in the Milky Way.

Beginning with lecture 3, the course focuses on specific objects in the disk of the Milky Way that trace how stars form and evolve:

- Beginnings of star formation: The Horsehead Nebula is the most well-known dark cloud of interstellar stardust. Viewing it in the near-infrared with Hubble enables you to partially see through the stardust and trace the intricate cloud structure and beginnings of star formation within the nebula.

- A newborn star: Hubble's sharp view of another dark cloud reveals outflowing jets of gas from a newborn star. As these amazingly narrow jets impact the surrounding gas, they produce knotty clumps of nebulosity known as Herbig-Haro objects.

- A young family of stars: A visit to the Westerlund 2 star cluster provides an opportunity to witness and understand the birth and evolution of a young family of stars. The Hubble image of this cluster and its environment shows how the intense radiation and strong stellar winds of young, hot stars can illuminate and sculpt the nebular surface of their nearby parent cloud.

- Bubbles produced by stars: Hubble's vision has revealed the thin, wispy membrane of the Bubble Nebula in beautiful detail. Such gas bubbles can be produced through stellar winds and explosions and are found in a variety of sizes throughout the galactic interstellar medium.

- A variable star: A series of Hubble exposures reveals a sparkling nebula of stardust around a variable star. The science behind this story of light echoes, and stellar pulsations have implications reaching from the Milky Way to the most distant galaxies.

- An exploded star: Hubble's sharp view of the Veil Nebula reveals the thin, wispy remains of a massive star that exploded as a supernova about 10,000 years ago. Such remnants are the primary galactic source of atomic elements like oxygen that have made life on Earth possible.

Beginning with lecture 9, the course's focus turns to a larger-scale view of the Milky Way as a galaxy. At the galactic center, Hubble has seen through much of the intervening stardust to reveal a massive star cluster with a central stellar density that is a million times greater than that in the solar neighborhood. An even denser core of darkness in the form of a supermassive black hole resides at the core of this cluster.

The disk of the Milky Way is surrounded by a sparse halo of stars and globular star clusters. Hubble's sharp view has separated the densely packed stars in the largest globular and helped to illustrate the dynamic role of these clusters in shaping the galactic halo.

Just beyond the galactic halo, there are dozens of small satellite galaxies orbiting the Milky Way. Hubble has explored an intense star-forming region inside the largest of these satellites, the Large Magellanic Cloud (LMC). This starburst can be understood in the context of the LMC's gravitational interactions with another satellite galaxy, the Small Magellanic Cloud.

The final lecture investigates the future coevolution of the Milky Way with the Local Group of neighbor galaxies, using Hubble images of distant galaxies whose dramatic collisions are already visible. The Milky Way's future collision with the Andromeda Galaxy will be a transformative event that changes the very essence of our night sky.

Lecture 1

THE UNSEEN FACE OF OUR SPIRAL GALAXY

The Milky Way glows with the light of 300 billion stars, dimmed by vast clouds of interstellar gas and stardust. And new stars just keep forming—roughly 1 new star every year! The Milky Way is one among many billions of spiral galaxies in a universe that stretches billions of light-years in every direction. With the Hubble Space Telescope, we can see details in distant spirals that mirror the vast star-making capabilities of our own galaxy. Its spiral structure both stimulates and reflects a galaxy-wide process that has been recycling matter between stars and the interstellar medium for the past 13 billion years.

The Vastness of the Milky Way

- Astronomers typically use units of light-years to measure vast spaces in the universe. One light-year is equal to the distance that light travels in 1 year at its speed of 300,000 kilometers per second (km/s). That distance is equal to 6 trillion miles, or more than 9 trillion kilometers. In comparison, the 150-million-kilometer distance between the Earth and the Sun is about 8 light-minutes. On this scale, the distance between the Earth and the Moon is about 1 light-second.

- In contrast to these relatively nearby solar system distances, the nearest star system, Alpha Centauri, is 4.3 light-years away, or 270,000 times the distance to the Sun. Most of the Milky Way's 300 billion stars are in a gas-rich disk that measures 100,000 light-years across, with a thickness of about 2000 light-years. The solar system is located inside the disk at a distance of about 27,000 light-years from the galactic center.

- The vastness of the Milky Way means that almost all of it is only explorable by telescope. At optical wavelengths, the patchy distribution of dust restricts our telescopic view into the disk to distances less than about 6000 light-years in most directions. Above and below the disk, our optical view into the galactic halo and the space beyond is essentially unrestricted by the thin dust disk. The spherical halo surrounding the Milky Way has far less dust—and far fewer stars—than the disk.

> With a variety of evermore powerful cameras and spectrographs, Hubble has made more than a million recorded observations of the universe, with results published in more than 15,000 scientific papers.
>
> Even so, the space telescope has imaged only a small part of the entire sky to date with its unprecedented resolution.

- Given the size of the Milky Way and our inability to see it from outside, it's not surprising that up until the early 1920s, many astronomers believed that our galaxy constituted the entire universe. However, observations of the galactic halo region with small telescopes had revealed a puzzling population of nebulous objects exhibiting spiral shapes or elliptical symmetry. Since their distances were unknown, it was not clear if these nebulae were distant Milky Way star clusters like the globulars or island universes like the Milky Way itself at a far greater distance.

- The astronomer who solved this puzzle and began the exploration of a much larger universe was Edwin Hubble.

Edwin Hubble's Observations

- In 1919, when Hubble was offered a staff position at the Mount Wilson Observatory, the 100-inch telescope on Mount Wilson had recently been completed and would remain the largest telescope on the planet until 1949. He needed such a big telescope to better study the faint objects in the galactic halo.

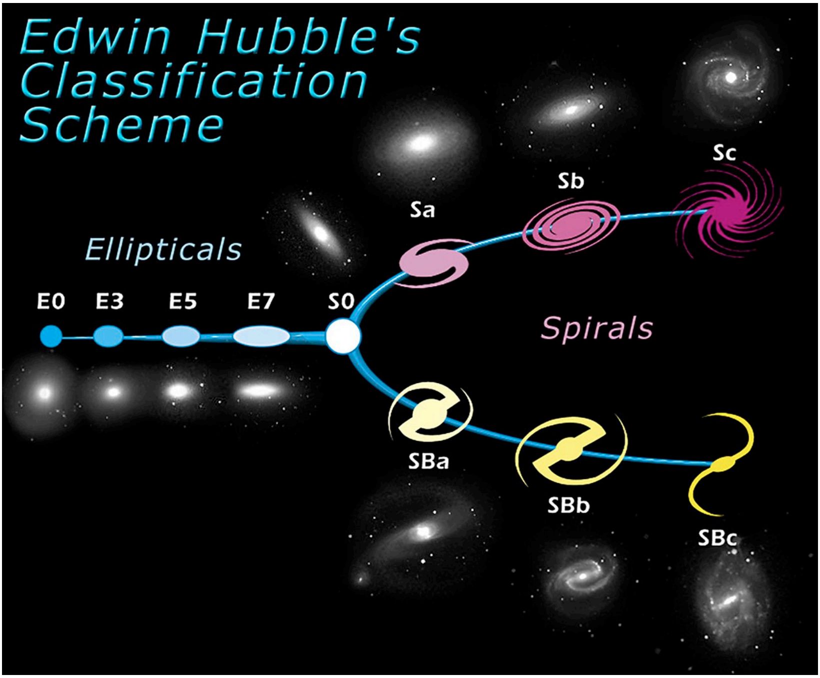
- Among these objects, then called nebulae, the brightest was known as the Great Spiral Nebula in Andromeda. This object became Hubble's key target in his quest to determine the distance and true nature of the so-called spiral nebulae. Using the 100-inch telescope, he was able to resolve out some of the bright stars in the Andromeda Nebula.

- His key breakthrough was realizing that some of these stars are actually pulsating stars known as Cepheid variables. The brightness variations of such stars can be utilized to determine their distances. In a landmark paper presented in 1925, Hubble showed that the Andromeda Cepheids indicate that what had been thought to be a spiral nebula is actually a galaxy of stars that is much farther away than the size of the Milky Way. At its distance of 2.5 million light-years, Andromeda is the nearest spiral galaxy to the Milky Way. With this discovery, the Milky Way is recognized as one galaxy out of many galaxies.

- As he continued his observations of the universe beyond the Milky Way with the 100-inch telescope, Hubble accumulated detailed photos of a variety of other galaxies. Overall, Hubble's Mount Wilson images revealed that the vast majority of large galaxies in the local universe exhibit either a spiral or elliptical morphology.

- Based on these images, he developed the so-called tuning-fork classification scheme for galaxies into elliptical and spiral [FIGURE 1.1]:
  - The elliptical galaxies range from spherical to more flattened and cigar-shaped. In general, all elliptical galaxies consist of old stars, lack abundant gas clouds, and have very little to no ongoing star formation.
  - The spiral galaxies typically feature both young and old stars, are rich with gas clouds, and have lots of ongoing star formation. Spirals are disk-shaped galaxies that are subdivided into 2 branches based on the existence or absence of a bar of stars running through their central bulges. Both of these spiral branches are further classified by their bulge sizes and the openness of their arms.

FIGURE 1.1



The formal names for galaxies typically come from their listing numbers in various catalogues of sky objects. A small number of bright galaxies have designations beginning with M that owes to their inclusion in the 18th-century Messier catalogue. A much larger list of galaxies appears in the 19th-century New General Catalogue with an NGC designation.

- In recognition of Hubble's many accomplishments in establishing that we live in a universe of galaxies, NASA named the yet-to-be-launched space telescope after him in 1983. It is quite fitting that with this space telescope, we can now image Hubble's galaxies in much greater detail and also compare them with close-up images of our own galaxy.*

The Search for a Milky Way Look-Alike

- In our search for a Milky Way look-alike, let's begin with this Hubble Space Telescope image of a pair of galaxies associated with the Virgo cluster of galaxies [FIGURE 1.2]. The elliptical galaxy M60 in the center and the spiral NGC 4647 in the upper right are separated on the sky by an angle equal to about 10% of the Moon's diameter. Although the 2 galaxies appear to overlap in their Hubble image, they are actually well separated in the third dimension by their respective distances of 54 and 63 million light-years.

- In comparing them, note in particular the bluish color of the spiral and the dark patches of its dust lanes. The bluish color is a telltale indicator of hot, luminous young stars. In contrast, the elliptical is essentially featureless except for its bright core. It shows no evidence of dust and lacks the blue signature of young stars indicative of ongoing star formation. Such comparisons between the 2 basic types of large galaxies show that the Milky Way must be a spiral.

* With its 2.4-meter-diameter primary mirror, Hubble was designed to have a resolving power that was more than 10 times better than the largest ground-based optical telescopes when it was launched in 1990. Since then, it has been serviced 5 times with new instrumentation by the now-retired space shuttle fleet.

FIGURE 1.2

- Next, let's investigate a spiral in detail by zooming in with Hubble on the nearby barred spiral galaxy M83 [FIGURE 1.3]. At its distance of 15 million light-years, the face-on view of this galaxy with Hubble's sharp eye reveals remarkable small-scale structure in its colorful spiral arms.

FIGURE 1.3

- As viewed from afar, the arms are traced by the blue, pink, and brown colors. The blues come from the light of young star clusters dominated by the high luminosity of their hot, massive stars. The pinks are due to the glow of hydrogen gas in nebulae that are heated by the ultraviolet radiation from these hot stars. The browns are the clouds of thick stardust and dense gas where new stars are born. Taken together, these colors tell us that the spiral arms are the primary focus of star formation in M83 and other spiral galaxies.

- In a spiral galaxy, here's what the process of ongoing star formation is like. As a disk galaxy rotates, the gravitation between stars at different radii in the disk develops and maintains spiral waves of greater mass density. These spiral density waves rotate much more slowly than the stars and gas clouds in the disk. As the stars and gas approach a wave, they slow down, which compresses the gas clouds, and they begin to form new stars.

- Among these new stars, the hot blue ones will be by far the most luminous and will excite the pink glowing nebulae. As the gas clouds and young stars rotate through the density wave of a spiral arm, the star formation slows and the luminous blue stars die first. Thus, the spiral arms stand out with their characteristic blue color and associated pinks.

FIGURE 1.4

- Viewing the large-scale spiral structure in nearby galaxies like M83 is vital to understanding the structure of the Milky Way since the Milky Way is mostly hidden to us at optical wavelengths due to our inside perspective.

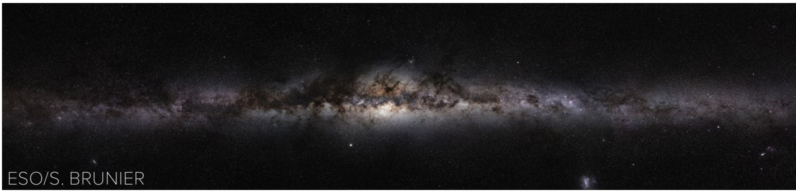
- The impact of the inclination angle on our view of a spiral galaxy can be seen in the Hubble image of the galaxy pair NGC 4302 and NGC 4298 in the Virgo galaxy cluster [FIGURE 1.4]. Both of these spirals are at the same distance of about 55 million light-years. The galaxy on the left is about twice the size of the smaller galaxy on the right but is seen almost exactly edge-on, with no view of its spiral structure. In contrast, with its inclination of 70°, the spiral face of the smaller galaxy is clearly evident.

- From a 3-dimensional perspective, each spiral galaxy could be circular and face-on or linear and edge-on. It's easy to model the edge-on view of a face-on spiral; it's much harder to use an edge-on view to model a face-on view. Yet the edge-on view is all we have to model our Milky Way Galaxy.

- Let's now compare the edge-on view of NGC 4302 [FIGURE 1.5] to our local, inside view of the inner Milky Way [FIGURE 1.6]. Both of these large-scale optical views look remarkably similar—a long band of diffuse light with large patches of thick dust. In other words, our inside view of the Milky Way is similar to that of an edge-on spiral galaxy.

FIGURE 1.5

FIGURE 1.6



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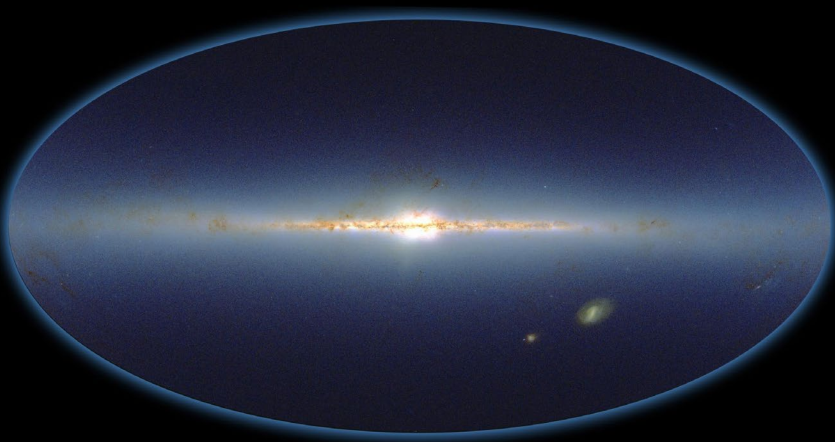
- In searching for a spiral galaxy with a face like the Milky Way, we get an additional clue from our inside view of the shape and size of the stellar bulge surrounding the galactic center [FIGURE 1.7]. At near-infrared wavelengths, just beyond the optical, it becomes possible to see this starlight through much of the intervening dust in the galactic disk. This near-infrared survey of the entire sky was taken with a ground-based telescope and reveals the central stellar bulge of the Milky Way.

FIGURE 1.7



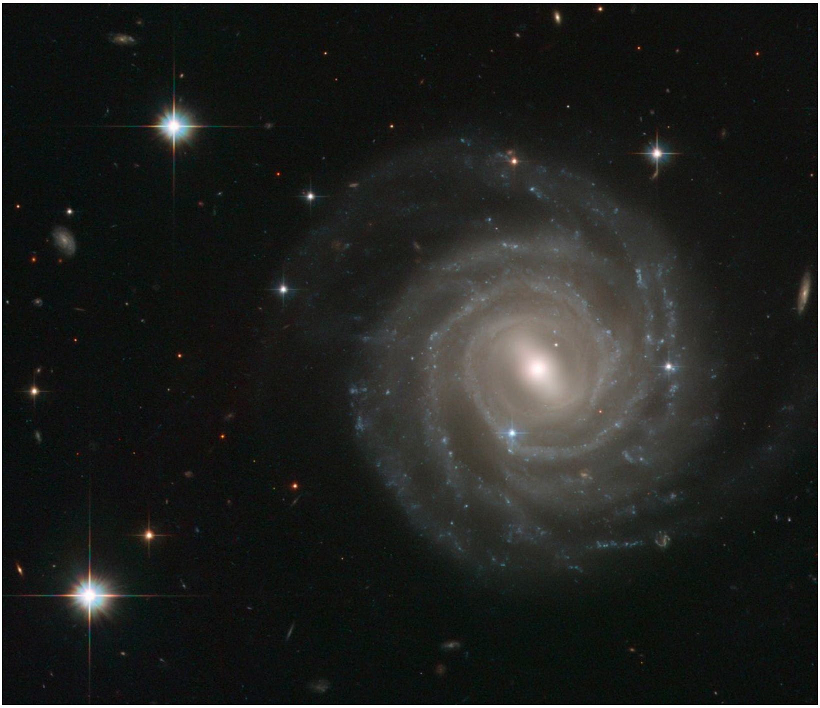
Near-infrared all-sky survey

- Such a bulge implies that our galaxy is a barred spiral. About ½ of all spirals have these bar-shaped stellar concentrations at their centers. It is believed that such bars form when stars near the center are gravitationally perturbed into elliptical orbits. These bars may be a temporary feature that comes and goes over billions of years as spiral galaxies age and evolve.

- The Hubble Space Telescope has observed a number of face-on barred spiral galaxies over the years and has shown that just like snowflakes, no 2 barred spirals are exactly alike.

- Among all of the face-on barred spirals imaged by Hubble, this view of the galaxy UGC 12158 comes closest to what we think the Milky Way would look like face-on [FIGURE 1.8].† UGC 12158 appears to be a close match to the Milky Way based on its distinct spiral arm pattern and the relative sizes of its disk, bulge, and bar. The only significant difference is that it's about 40% larger than our galaxy. A key feature that's revealed in the Hubble image are the many small blue patches in the arms. Given the galaxy's large distance of 400 million light-years, these patches correspond to young star clusters. Such clusters can also be used to trace the spiral arms in the Milky Way.

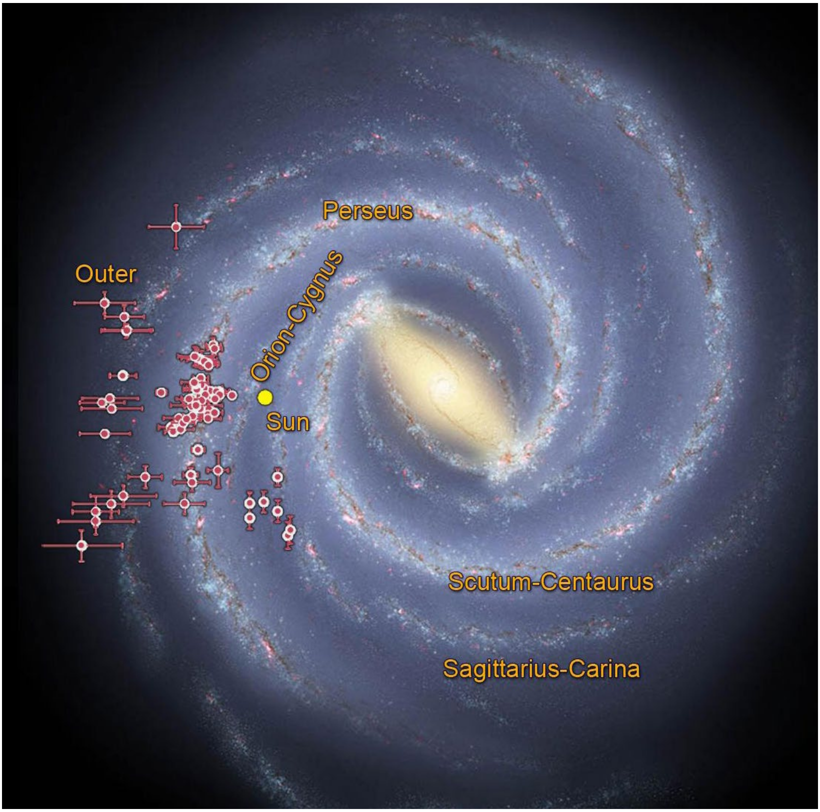
FIGURE 1.8



† This galaxy is number 12,158 in the Uppsala General Catalogue of Galaxies, which includes a total of 12,921 galaxies visible in the northern sky.

- Here is a model of the Milky Way's face-on spiral structure [FIGURE 1.9]. The model is based on a variety of observations, from optical to radio wavelengths. In particular, the red points are young star clusters identified through an infrared space observatory survey of the entire sky. These clusters outline nearby parts of 3 spiral arms of the Milky Way: the Outer, Perseus, and Sagittarius-Carina arms. Our solar system is located between the Perseus and Sagittarius-Carina arms.

FIGURE 1.9



READINGS

Bartusiak, *The Day We Found the Universe*.

Bland-Hawthorn and Gerhard, "The Galaxy in Context."

Christianson, *Edwin Hubble*.

Hubble, *The Realm of the Nebulae*.

QUESTIONS

1. What would the night sky look like to the naked eye if the Earth were positioned directly above the galactic center at the same distance that it is currently located away from the center in the galactic disk?

2. How might you determine whether a distant, elongated galaxy as viewed with the Hubble Space Telescope is a cigar-shaped elliptical or an edge-on spiral?

VIEWING THE GALAXY THROUGH A COMET

A single image of the night sky can explore a depth of distance so vast that it provides a window from the present to the distant past. A spectacular example of such depth in an astronomical image is provided by Hubble's view of Comet ISON when it was located inside the orbit of Jupiter at a distance of 36 light-minutes from Earth. This comet image is unusual in that it is composed of multiple exposures that tracked and focused on the background stars rather than the comet as it moved with respect to the stars. The net result is a Hubble showcase of Comet ISON displayed against an incredibly sharp, deep background of faint galaxies stretching beyond a billion light-years.

The Motion and Distance of Solar System Objects

- It is common to express distances of objects in the solar system in terms of astronomical units (AU). On this scale, the distance between the Earth and the Sun is defined as 1 AU. The Earth orbits the Sun at this distance, with a speed equal to 30 km/s, or about 30 times the speed of a rifle bullet.

- Over the course of 1 year, the Sun appears from Earth to make a complete circle around the sky with respect to the stars. This path around the sky is called the ecliptic.*

The ecliptic passes through 12 of the 88 established star constellations that encompass the entire sky. Despite their apparent proximity on the sky, the stars making up a constellation can have distances ranging from tens to thousands of light-years. Thus, the stars in a constellation are typically too far apart to be physically associated with one another.

Due to their great distance, the stars also move very slowly relative to each other on the sky. Consequently, the star patterns embedded in the constellations have not changed appreciably for thousands of years. As a result, the star constellations have been and continue to be a convenient way to navigate the sky.

- The other 7 planets in the solar system follow nearly circular orbits around the Sun in essentially the same orbital plane as the Earth. Thus, as viewed from Earth, the planets also appear to move along the ecliptic with respect to the stars. Mercury and Venus orbit closer to the Sun and move faster in their orbits, with shorter orbital periods, than does the Earth. Mars orbits the Sun every 1.9 years at a distance of 1.5 AU. It takes Jupiter 12 years to circle the ecliptic at its distance of 5 AU. The outer planets move even more slowly in their orbits.

* Note that this yearly motion of the Sun with respect to the stars due to the Earth's orbit is quite distinct from the daily rising and setting of the Sun and the stars on the sky due to the Earth's rotation.

> A comet is a product of the solar system that can rival the Milky Way in apparent brightness with a lengthy tail across the sky.

- Unlike the planets, most comets follow sky paths outside the ecliptic. The nucleus of a typical comet is a few kilometers in size and made mostly of ice with some rock. It is estimated that there are trillions of such cometary nuclei in the outer solar system. They are essentially the leftover debris from the formation of the planets around the newborn Sun 4.6 billion years ago.†

- Most of these kilometer-sized objects are now collectively orbiting the Sun in a spherical shell at a distance of roughly 50,000 AU. This distant reservoir of cometary nuclei is known as the Oort cloud. Although vast in size, its total mass is likely less than 10 Earth masses. A smaller but closer source of comets is the so-called scattered disk of icy objects lying along the ecliptic beyond Neptune out to a distance of about 100 AU.

- In terms of the known planets, the radius of the solar system is 30 AU, or about 4 light-hours. We have now sent spacecraft to all of these planets plus Pluto, the dwarf planet orbiting the Sun at an average distance of 40 AU.

- Our most distant space probe, Voyager 1, was launched in 1977 and is now more than 150 AU away, traveling through interstellar space. Voyager 1 will reach the Oort cloud in about 300 years and take 30,000 years to pass through it.

- The nearest star system, Alpha Centauri, is at a distance of 270,000 AU—5 times farther away than the Oort cloud. It turns out that the average distance between stars in the Milky Way's disk is about a million times greater than that between Earth and its nearest planetary neighbors.

- Given their tiny size, cold temperature, and distance from the Sun, individual cometary nuclei in the Oort cloud and scattered disk are far too faint to detect even with Hubble. However, due to gravitational perturbations, a few of these icy objects lose orbital energy over time and begin a long fall into the gravity well of the inner solar system.

† Due primarily to gravitational interactions with Jupiter, whose mass is greater than that of all the other planets combined, this icy debris was scattered out to orbits far beyond Neptune.

- As such an object approaches the Sun, the solar gravity and radiation increases its velocity and starts defrosting its icy exterior. As these ices begin to vaporize, they form a glowing cloud of gas and dust around the nucleus of the comet. This so-called coma begins to develop when the comet is about 5 AU away from the Sun. The coma can grow to a diameter of 100,000 kilometers and is thus much, much larger than the comet's solid nucleus.

- As the comet gets within a few AU of the Sun, the solar wind of charged particles is strong enough to push some of the coma gas into a tail. This characteristic gas tail of a mature comet can reach 1 AU in length and always points away from the Sun as the comet continues in its orbit.

- The maximum brightness of a comet as viewed from Earth depends on many factors, ranging from the size of the comet's nucleus to how close it gets to both the Sun and the Earth.

- A bright comet visible to the naked eye appears on the sky about every 3 years. Such a comet can be tracked across the sky by eye for weeks to a month or more. The appearance of a comet on the sky is thus quite different than that of a typical sand grain–sized meteor, whose streaking flash lasts less than a second as it burns up while entering Earth's atmosphere.

- Depending on an incoming comet's size, velocity, and trajectory, it can have a variety of fates. If the comet passes too close to the Sun, it can be tidally ripped apart or actually fall into the star. If the comet survives solar passage, its trajectory may take it out of the solar system forever or put it into a long-term orbit back toward the Oort cloud with a return date measured in thousands to millions of years.

- However, if the comet's path takes it close to Jupiter, the giant planet's gravity can perturb the comet into an orbit with a much shorter period, which keeps it in the solar system. The most well-known example of such an object is Halley's Comet, which has been orbiting the Sun every 75 years for thousands of years and will make its next appearance on the sky in 2061.

Comet ISON

- Astronomers all over the world continue to scan the sky nightly looking for new comets. In this manner, Comet ISON was discovered in September 2012 by Russian astronomers associated with the International Scientific Optical Network (ISON).‡

- The discovery image of ISON revealed a very faint fuzzy object indicative of a comet coma but without an obvious tail. Comparisons with subsequent and previous images of this sky region made it possible to quickly compute the position and orbit of the comet. The discovery position of ISON put it beyond Jupiter's orbit at a distance of 6 AU.

- With a non-ecliptic origin, the computed orbit for ISON indicated that it was a new Oort cloud comet. Tracking this orbit forward in time, it was clear early on that the comet would pass close to Mars on October 1, 2013, and even closer to the Sun on November 28, 2013. Indeed, ISON was quickly classified as a sungrazing comet because its closest approach to the Sun would be about a million kilometers.

- Most sungrazers are faint with small nuclei and typically don't survive their close solar passage. On the other hand, some of the brightest comets have been sungrazers. With core sizes of at least a few kilometers, these comets could withstand the close solar passage that allowed them to reflect much more light.

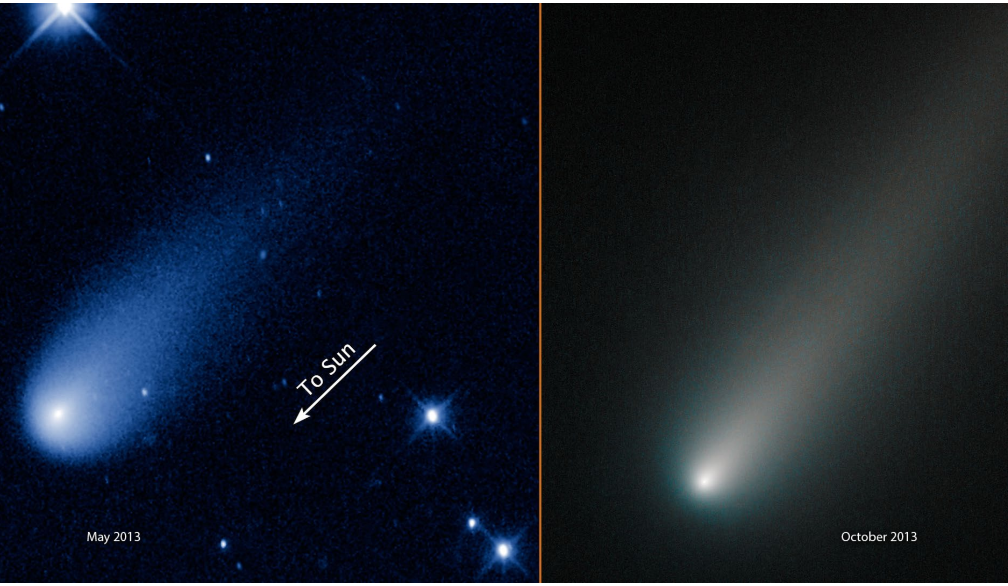
- Early indications based on its initial brightness were that Comet ISON might be large enough to join this select group. Thus, predictions soon followed that ISON could be visible to the naked eye even in the daytime sky just after solar passage.

- Consequently, excitement and anticipation built for Comet ISON during 2013. Some media outlets began to advertise it as the "comet of the century." Sky maps were posted for the public to track ISON among the star constellations as it brightened and moved faster across the sky toward its solar rendezvous in late November.

‡ This network, for which the comet was named, is a group of ground-based observatories dedicated to surveying the sky for comets and other objects that move with respect to the stars.

- Hubble began to observe ISON well before it passed the orbit of Mars. A comparison of Hubble images taken in early May and early October of 2013 [FIGURE 2.1] shows the comet brightening and the tail lengthening from 120,000 to more than 200,000 kilometers as ISON's distance from the Sun decreased from 3.8 to 1.5 AU.

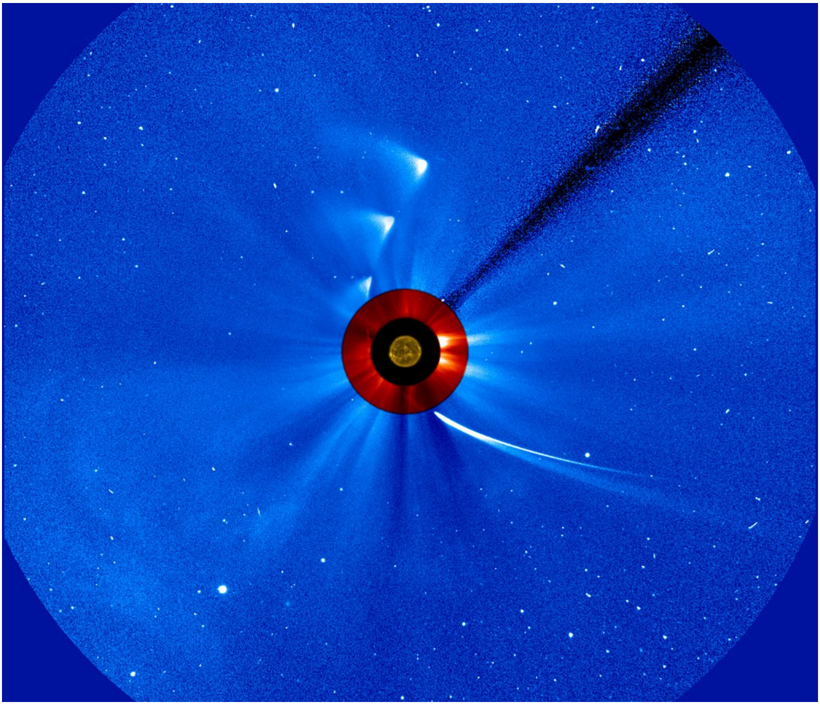
FIGURE 2.1



- By late November, the comet was faintly visible to the naked eye just before sunrise. As ISON subsequently got closer to the Sun, it became hard to see in the Sun's glare. Fortunately, NASA and the European Space Agency have solar observatories in space that can avoid the glare.

- This time-lapse photo [FIGURE 2.2] from the Solar and Heliospheric Observatory follows the clockwise path of ISON from the time of its closest passage on November 28th to December 1st. Although the direct view of the bright Sun is blocked by a central mask, the photo clearly shows that the comet breaks up at solar passage. Pieces of ISON survive the passage, but the comet quickly fades as it rounds the Sun. If it had survived intact, a much brighter comet would have emerged instead.

FIGURE 2.2



- The bottom line is that Comet ISON was not big enough and compact enough to survive so close to the Sun's heat and tidal force. Later analysis showed that the nucleus of ISON was much smaller than originally thought. Comets originating from the Oort cloud often appear brighter initially than they should for their size due to the burning off of their ice-rich exteriors.

- Although Comet ISON did not end up as the "comet of the century," its early Hubble image lives on as a beautiful depiction of a comet as a cosmic voyager amid a vast sea of stars and galaxies.

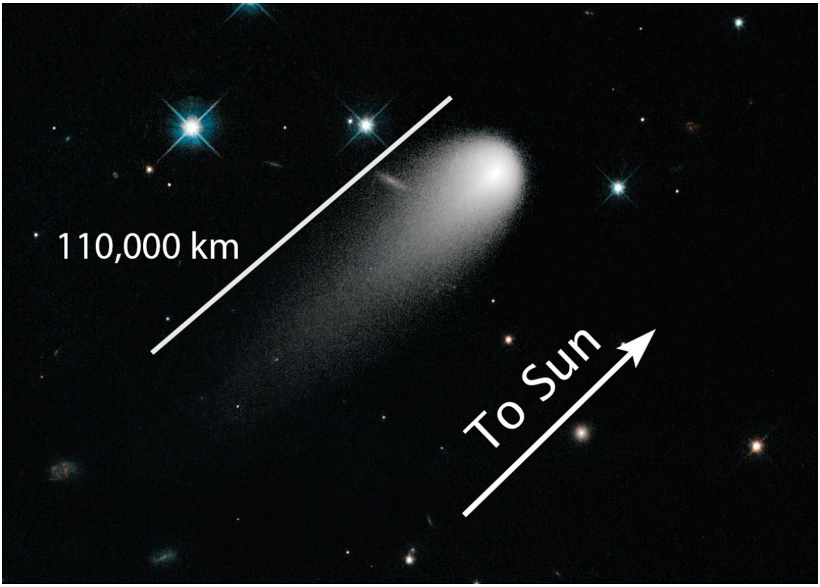
- When this image [FIGURE 2.3] was taken 7 months prior to its breakup, ISON had already passed the orbit of Jupiter and was 3.9 AU away from the Sun. It was still faint enough for Hubble to contrast its appearance with faint background galaxies.

- At this time, the young tail of the comet had reached a length of 110,000 kilometers—about 30% of the distance between the Earth and the Moon. The total sky area of the Hubble image is equal to about 1% that of the Moon.

FIGURE 2.3

- Zooming in on the comet reveals more remarkable detail. The 3 stars near the top of this close-up [FIGURE 2.4] are at distances ranging between hundreds and thousands of light-years in the Milky Way. Among the faint background galaxies, the edge-on spiral partially eclipsed by the coma of Comet ISON is more than a billion light-years away.

FIGURE 2.4



- The key to bringing out the depth of background detail in the Hubble image was the telescope tracking on the stars instead of the comet.

- The image is actually a composite of a 5-exposure sequence. Each exposure was either 440 or 490 seconds in length. From beginning to end, Hubble spent 46 minutes on target. During that time, it moved 13,000 kilometers in its orbit around Earth.

- Hubble tracked on the background stars; they didn't move from exposure to exposure. The apparent comet movement has 2 components: the comet's motion with respect to the stars as it moves toward the Sun, and Hubble's motion in its 96-minute orbit around the Earth, which slightly shifts the apparent position of the nearby comet with respect to the distant stars.

- Thus, when the exposures are combined, the background is sharp but the comet is fuzzier, with apparent multiple bright nuclei in a larger coma. This visual effect in one of the original press release images led to some UFO enthusiasts claiming that it proved that Comet ISON had an extraterrestrial escort!

- This featured Hubble ISON image has been processed to most accurately portray the comet and the background in the same view. The 5 exposures were combined to better see the faintest background objects. The comet itself is based on just one exposure to minimize any fuzziness due to the tracking issue.

- Observing comets is truly a matter of perspective. The focus and the track are almost always on the comet itself to bring out its details. In the case of the Hubble ISON image, the focus is on the background depth behind the comet.

READINGS

Bland-Hawthorn and Gerhard, "The Galaxy in Context."
Chambers and Mitton, *From Dust to Life*.
Eicher, *Comets!*
Seargent, *The Greatest Comets in History*.

QUESTIONS

1. Why can the Hubble Space Telescope observe comets and asteroids on the sky but not meteors (also known as falling stars or shooting stars)?

2. Estimate the orbital distance that the Sun travels per year around the galactic center. How does this distance compare to that traveled by Comet ISON during the final year of its approach to the Sun?

Lecture 3

A CLOUD OF STARDUST: THE HORSEHEAD NEBULA

The space between the stars is not empty. It is partially filled with clouds of interstellar matter consisting of both gas and solid grains of stardust. It is inside the darkest and densest of such dust clouds that new stars are born. The most famous of these dark nebulae is the Horsehead Nebula in the constellation Orion. It is located near the eastmost star in Orion's belt at a distance of 1500 light-years. As viewed at optical wavelengths, the horsehead shape of the densest stardust region extends 2 light-years above the cloud base. It is seen in silhouette as the dust blocks the background light of a glowing gaseous nebula. Viewing the Horsehead Nebula in the near-infrared with the sharp eye of Hubble enables us to partially see through the stardust and trace the intricate cloud structure and beginnings of star formation within the nebula.

Star Formation in Nebulae

- The disk of a spiral galaxy is essentially a star-making machine. As seen in this Hubble view of the galaxy M83, the star formation in a disk galaxy is concentrated in its spiral arms [FIGURE 3.1]. And the colors tell the tale. The brown filaments trace the locations of the densest dust clouds, which both block the light of background stars and incubate the next stellar generation. The blue sprinkles are clusters of luminous hot stars that recently formed from dusty clouds that are now being evaporated by the intense radiation and strong winds of these stars. The pink patches are the glowing gaseous remnants of these clouds, heated by the nearby young stars. These colors are thus linked together in tracing the arms of a spiral galaxy in terms of star formation.

- This linkage can be considered as part of a natural recycling process in spirals that cycles matter back and forth between the interstellar medium and stars. The cycle begins with a dark molecular cloud of gas and stardust that is so cold and dense that most of the gas is in the form of molecules. When the cloud is compressed by a spiral density wave or a nearby supernova explosion, clumps of gas within the cloud will gravitationally contract and begin to form stars.

FIGURE 3.1

- Over the course of about 10 million years, such a star-forming region typically produces hundreds to thousands of stars. Most of these stars have masses that are less than the Sun, but a few can reach a mass of 50 Suns or more.

- Over the course of millions to billions of years, the nuclear fusion powering these stars will steadily convert hydrogen to heavier elements in their cores. As the most massive stars evolve quickly over a few million years, their strong winds and eventual supernova explosions break up the parent molecular cloud into mostly diffuse atomic gas. The supernova remnants also add enhanced abundances of heavier elements into this atomic interstellar gas. Over time, some of this atomic gas is swept into new molecular clouds through galactic rotation and stellar outflows.

- The cycle then repeats itself with molecular clouds that have been enriched with slightly higher abundances of heavy elements. The elemental composition of the solar system today reflects billions of years of such stellar-enrichment cycles that occurred before the solar system formed 4.6 billion years ago. This stellar-recycling process has steadily built up the abundances of elements like carbon, nitrogen, oxygen, iron, and silicon to the point where rocky planets can easily form in the Milky Way and life has existed on at least one of them for about 4 billion years.

- In terms of the mass composition of the interstellar medium today, 99% of it is made of gas and 1% consists of dust grains.* The total mass of interstellar gas and dust in the galaxy is about 15% of that in stars.

- The diffuse atomic gas in the interstellar medium becomes visible at optical wavelengths when it is illuminated by a nearby hot star. The ultraviolet light from such a star can be intense enough to ionize the surrounding interstellar atomic hydrogen into its constituent protons and electrons out to distances of a few light-years.

- When these protons and electrons collide and recombine into hydrogen, the new atoms radiate away some of their energy in the form of optical light. The spectrum of light emitted by hydrogen atoms is optically brightest at a specific red wavelength. Consequently, color images of gaseous nebulae typically appear red or pink.

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* Atomic and molecular hydrogen together account for 75% of the mass in the interstellar gas. Helium accounts for 24%, and all of the other elements together add up to just 1% of the interstellar gas.

- Overall, the average density of gas in the galactic interstellar medium is about 1 hydrogen atom per cubic centimeter. The gas density in the densest molecular clouds can reach a million atoms per cubic centimeter. In comparison, the density of Earth's atmosphere at sea level is higher by a factor of 10 trillion. Of course, the molecular clouds make up for this density deficit by being light-years in size compared to Earth's diameter of 1⁄25 of a light-second. Overall, the molecular clouds fill about 2% of the volume in the galactic disk. These gas-rich clouds also have the highest density of interstellar dust.

- Unlike the gas, the dust is in the form of solid grains of molecules abundant in elements heavier than hydrogen and helium. A typical interstellar dust grain consists of about a billion atoms distributed in a molecular core and surrounding mantle.†

- In terms of their light-scattering properties, these dust grains act collectively like the soot particles that make up smoke and smog in the Earth's atmosphere. With similar submicron sizes, the interstellar grains and the soot particles both scatter blue light more than red light out of the beam of a background light source. Thus, just like the Sun looks red when viewed through a smoke cloud, interstellar dust can make the colors of background stars look redder.

The Horsehead Nebula

- Amid the bright young stars of the constellation Orion is a large and complex region of interstellar gas and dust. In this deep ground-based optical image utilizing a red hydrogen filter, multiple gaseous nebulae are revealed throughout Orion [FIGURE 3.2].

- The large arc-like red nebula on the lower left is known as Barnard's Loop. Its angular extent on the sky is about 20 times the Moon's angular diameter. At the Loop's distance of 1500 light-years, this angular width corresponds to a size of 300 light-years. The Loop is part of an expanding shell of gas produced by a supernova explosion about 2 million years ago.

† The average size of an interstellar dust grain has been observationally determined to be about ½ a micron.

FIGURE 3.2

- Zooming inside Barnard's Loop, we see the Horsehead Nebula just below the eastmost star in Orion's belt [FIGURE 3.3]. This nebula is part of a giant molecular cloud (GMC) known as Orion B. This dark cloud is more than 100 light-years in extent with a total mass of 100,000 Suns.

FIGURE 3.3

- Zooming in farther, we can trace the footprint of the dark cloud based on star counts across the image [FIGURE 3.4]. Specifically, note that from the middle of the image to the lower left, there are fewer stars than above. The dark Horsehead Nebula is a patch of thick dust rising above the surface of the main dark cloud. The red glow partially illuminating the surface of the dark cloud and the diffuse gas above are due to ionized hydrogen. This gas is ionized by the ultraviolet radiation coming from the multiple star system Sigma Orionis located directly above the Horsehead.

FIGURE 3.4

FIGURE 3.5

- The installation of a new camera known as the Wide Field Camera 3 (WFC3)‡ with a sensitive near-infrared detector during the final servicing mission of the space shuttle in 2009 made it possible for Hubble to sharply see deeper into dusty regions such as the Horsehead Nebula.

- The WFC3 near-infrared view of the Horsehead Nebula reveals small-scale wispy structure and density contrasts throughout this optically dark nebula [FIGURE 3.5]. The image§ spans 2.5 light-years, with the Horsehead itself extending about 2 light-years above its dark cloud base. The shorter-wavelength near-infrared color is shown as blue in the image and the other near-infrared color as orange. In this combined color scheme, the regions with thicker dust look brown and those with thinner dust look blue.

‡ This camera has 6 times the field of view and 16 times the pixels of Hubble's first-generation near-infrared camera.

§ This image is the sum of 18 separate exposures in 2 near-infrared colors spanning a total exposure time of 6.3 hours.


FIGURE 3.6

- In comparison, this near-infrared contrast in the dust density is also reflected in the optical Hubble image of the Horsehead [FIGURE 3.6]. In the thinner dust regions, Hubble can see some optically invisible background stars. In the thickest dust regions, not even Hubble's near-infrared view can reveal stars behind the dust screen.

- The dust at the top of the Horsehead is thinning due to its direct exposure to the ultraviolet radiation from Sigma Orionis. This radiation is slowly evaporating the dust in the nebula from the top down. For a while longer, the dense dust in the head and mane of the Horsehead will continue to shield its neck down to the cloud base from the incoming ultraviolet radiation.

- The structure deep inside dense dark clouds like the Horsehead Nebula can be probed with observations at submillimeter and radio wavelengths. These 2 forms of light are part of a broad spectrum of electromagnetic radiation that includes ultraviolet, optical, and near-infrared light.

- The optical light that we see with our eyes is a tiny fraction of this spectrum. Its color spectrum from violet to red covers a wavelength range from 400 to 700 nanometers.¶ Each region of the electromagnetic spectrum provides a different view of the Milky Way that can aid in our understanding of the physical processes governing its stars and nebulae.

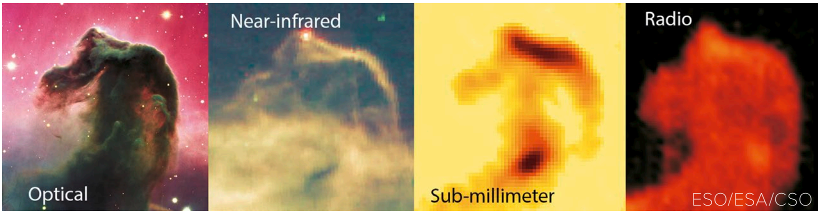
- In the case of a dark nebula like the Horsehead, its thick dust shields the interior from the ultraviolet radiation of nearby hot stars. Consequently, the cloud interior is very cold, with a temperature that's only 10° to 20° above absolute zero. Such cold, dense, dark regions are ideal for molecules like molecular hydrogen (H_2) and carbon monoxide (CO) to form in great abundance. That's why dark clouds are often called molecular clouds.

¶ One nanometer is equal to one-billionth of a meter.

- Best of all, molecules like CO emit radio waves, whose long wavelengths enable them to pass right through even thick dust. Consequently, with radio observations tuned to the CO wavelengths, it is possible to map the molecular interior of the Horsehead. Its radio CO image has a horsehead shape similar to that seen in the Hubble optical and near-infrared images of the dust.

- With observations at submillimeter wavelengths in the microwave part of the spectrum, the densest regions of dust and gas become apparent inside the Horsehead's top and neck.

FIGURE 3.7



- It is in such regions that the slow gravitational contraction toward star formation has begun. The initial contraction may have been triggered by a supernova shockwave like the one evident in Barnard's Loop. The dense clumps were originally light-years in size and rotating quite slowly. As the clumps contract, they slowly warm and spin faster due to the conservation of angular momentum. After about a million years, a clump will condense into a 100 AU–size disk of gas and dust around a protostar, which becomes a star when its dense core is hot enough to ignite the nuclear fusion of hydrogen into helium.

Over the next few million years, the Horsehead will evaporate after producing several more stars. Along the way, these new stars will evolve from dynamic protostars with dusty disks into mature stars with planetary systems.

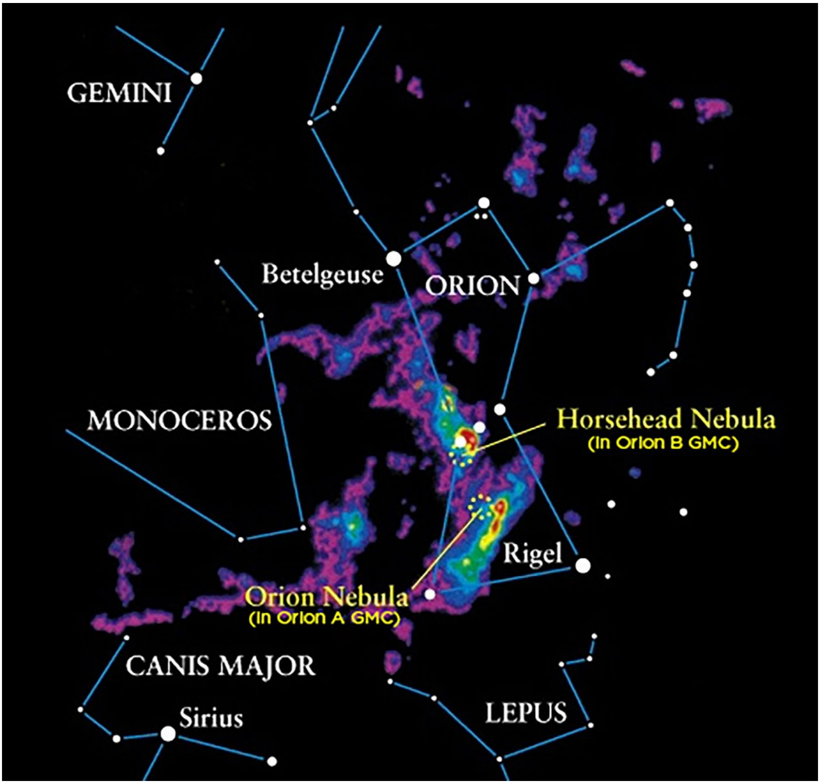
- Although the dust is too thick to see such protostellar disks inside the Horsehead with Hubble, another nearby molecular cloud in Orion provides a window into its star-making activity.

The Orion Nebula

- As seen in this radio map of dense CO gas in the Orion constellation [FIGURE 3.8], the Orion Nebula is associated with the giant molecular cloud Orion A. Like Orion B, this GMC is more than 100 light-years in extent and has a total mass of 100,000 Suns.

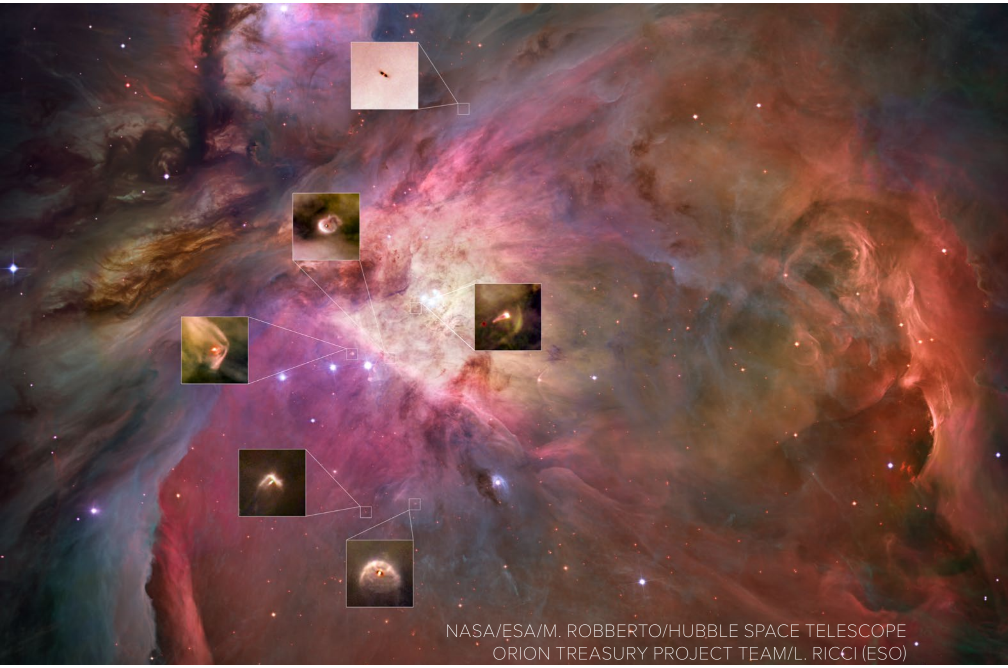
- The Orion Nebula is the brightest gaseous nebula on the sky and is actually visible to the naked eye below Orion's belt. At its core are 4 hot, young stars called the Trapezium that have carved a hole in the Orion A GMC that faces toward Earth. Their ultraviolet radiation is exciting the red glow in the surrounding nebular hydrogen.

FIGURE 3.8



- This Hubble optical image of the Orion Nebula [FIGURE 3.9] is 13 light-years across. It shows turbulent small-scale structure in both the diffuse gas and the dust in the nebula. It also reveals a number of protostellar disks in various evolutionary stages and at different inclinations to our line of sight. The radiation and winds of the Trapezium stars are evaporating the closest disks in their vicinity and causing some to take on a cometary appearance. The dusty protoplanetary disks that are far from the Trapezium likely will eventually evolve into planetary systems like the solar system.

FIGURE 3.9



- Studies of Orion and other GMCs show that star formation is very inefficient. Over the course of a typical 20-million-year GMC lifetime, only a few percent of the GMC mass is actually converted into stars. This low percentage is due in part to magnetic fields and turbulence in the clouds that slow or prevent gravitational contraction into stars.

- Another key factor is the rapid evolution of the first generation of massive stars in a GMC. Within a few million years, the radiation, strong winds, and supernova explosions of such stars begin to stir up and eventually break up the dense gas and dust of a GMC. Nevertheless, the process continues as new GMCs form from the diffuse debris of old GMCs. Thus, ongoing star formation in the Milky Way is due in part to its inefficiency.

READINGS

Bally and Reipurth, *The Birth of Stars and Planets*.
Beech, *The Pillars of Creation*.
Chambers and Mitton, *From Dust to Life*.
Kwok, *Stardust*.

QUESTIONS

1. If the Horsehead Nebula and its associated dark cloud were 100 times closer to the Sun, how would it change the appearance of the night sky as viewed with the naked eye from Earth?

2. If the star formation process were 10 times more efficient in converting interstellar gas and stardust into stars, what would the Milky Way look like today? What if it were 10 times less efficient?

A STAR AWAKENS: THE JETS OF HERBIG-HARO 24

On its way from initial collapse to the development of a planetary system, a developing star typically goes through a short-lived stage where its accretion of infalling matter is vigorous enough to feed bipolar gas outflows. One of the most photogenic examples of this phenomenon can be found just above Orion's belt in the same Orion B molecular cloud that features the Horsehead Nebula. Hubble's near-infrared view of this region reveals 2 narrow beams of light aimed in opposite directions from a source hidden behind a patch of illuminated dust. Astronomers refer to this object as HH 24, where the HH stands for Herbig-Haro, the last names of codiscoverers George Herbig and Guillermo Haro. HH objects are small, knotty clumps of nebulosity produced by the impact of bipolar jets of outflowing gas on the surrounding interstellar medium.

> The Hubble press release described HH 24's narrow beams of light in terms of *Star Wars* imagery as a "cosmic, double-bladed lightsaber."

Bipolar Jets of Outflowing Gas

- Our understanding of star formation in the Milky Way is a framework built upon many individual snapshots in time of a multimillion-year process. A rich star-forming region like Orion is a great place to start in providing such a synthesis.

- This wide near-infrared view of the Horsehead Nebula region [FIGURE 4.1] shows additional thick brownish dust patches near the center and lower left of the image. Along with the Horsehead, the interiors of these dark nebulae have gas clumps with the requisite high density to begin the initial steps toward gravitational collapse.

FIGURE 4.1

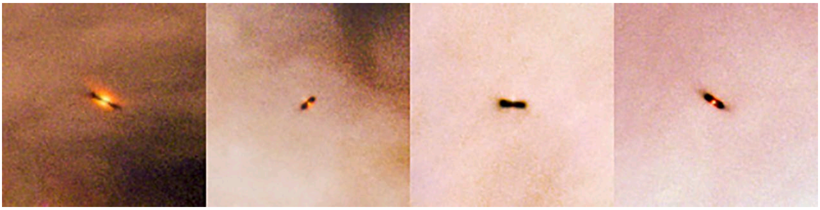


FIGURE 4.2

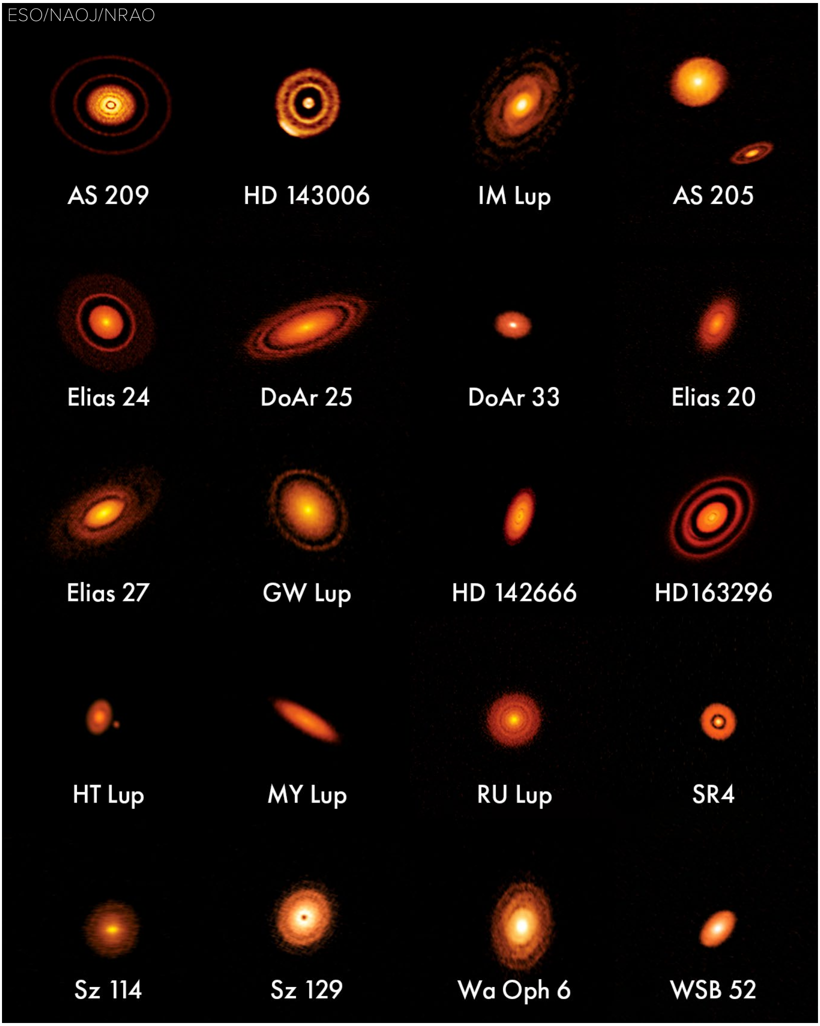
- Using the Orion Nebula as a bright diffuse background, Hubble has also revealed multiple examples of a later step in the star formation process [FIGURE 4.2]. Among its views of protoplanetary disks, such edge-on cases clearly show thick, dusty disks with an emerging star at their centers. Millimeter-wave observations can take the next step by directly imaging the dust emission in search of disk structure indicative of planet formation.

- In 2018, the Atacama Large Millimeter/submillimeter Array (ALMA) in northern Chile imaged a number of the nearest protoplanetary disks [FIGURE 4.3], revealing a stunning variety of disks with rings and gaps of various sizes and orbits. The largest disks extend more than 100 AU from their host stars, with dust gaps closer than 10 AU in some cases. Such gaps are likely the dynamical signature of planets forming from the accretion of dust grains into larger and larger objects in the disk.

- Eventually, these protoplanetary disks are expected to evolve into something like the solar system. Unfortunately, neither Hubble nor any other telescope currently has the sensitivity to optically image any complete planetary system in the Milky Way. The stars are simply too bright and almost all of their planets too close and too faint to see directly in the stellar glare.

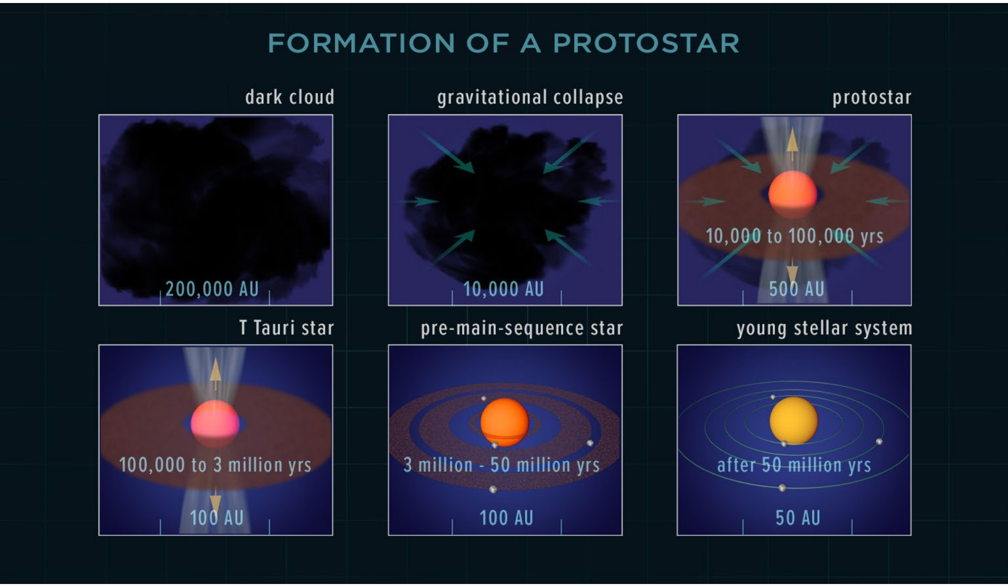
- Nevertheless, through indirect methods, astronomers have detected thousands of planets around a number of stars over the past few decades. Based on these results, it is likely that most of the stars in the galaxy have planetary systems. In other words, the process of star formation continues to make many more planets than stars in the Milky Way.

FIGURE 4.3


ESO/NAOJ/NRAO
AS 209
HD 143006
IM Lup
AS 205
Elias 24
DoAr 25
DoAr 33
Elias 20
Elias 27
GW Lup
HD 142666
HD163296
HT Lup
MY Lup
RU Lup
SR4
Sz 114
Sz 129
Wa Oph 6
WSB 52

- By utilizing theoretical models, it is possible to collectively link together the many observational snapshots of dark nebulae, protostars, and protoplanetary disks taken by Hubble, ALMA, and other telescopes. It results in a basic 6-step process for the formation of a 1-solar-mass star [FIGURE 4.4]. Overall, the process takes tens of millions of years, from the gravitational collapse of a cloud core to the formation of a star and its planetary system. The process is somewhat faster for a star that's more massive than the Sun and slower for a less massive star.

FIGURE 4.4

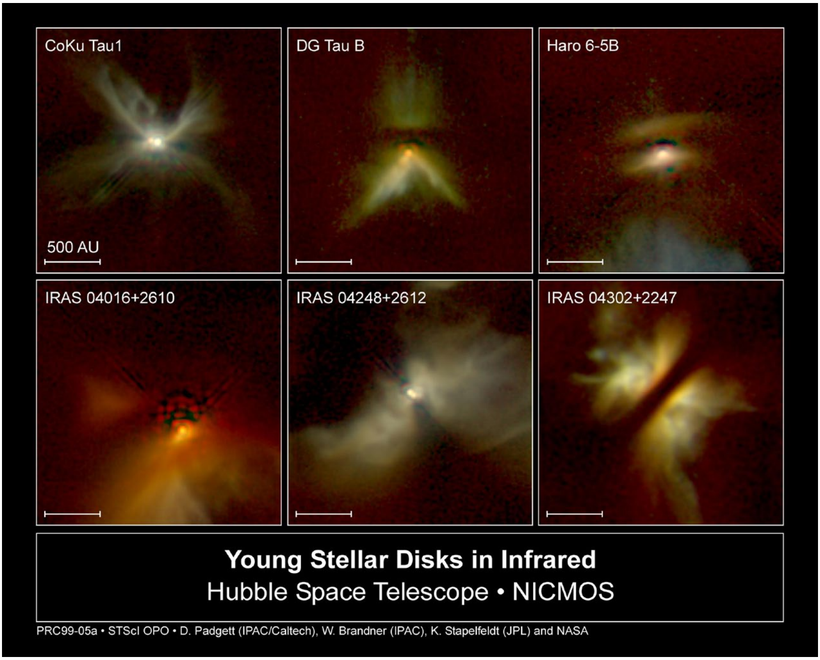


- A key step is the initial collapse to a protostar and its accretion disk. In a time frame of about 100,000 years, a roughly spherical cloud core with a radius of 10,000 AU collapses down to a central protostar and a surrounding disk of radius 500 AU. During this time, the protostar is accreting matter at a rate of about 1 Earth mass per year. As it gains mass, it becomes smaller in size with a higher gas density.

- Most of the infalling matter falls onto the protostar from the rotating accretion disk. Some of this infalling matter is blown back out by strong polar winds along the rotation axis of the protostar. These bipolar jets of outflowing gas are a key observational characteristic at this star formation stage. Indeed, it is typically through such outflows that the source is identified as a protostar. Since these sources are embedded in surrounding envelopes of thick dust, near-infrared or infrared observations are usually required to uncover the outflows.

- Starting with its first near-infrared camera called NICMOS, Hubble has observed the outflows associated with many protostellar disks. In the 6 cases shown here [FIGURE 4.5], the accretion disks are clearly evident in these edge-on views. At this stage in their evolution, the protostars shine as they heat up due to the gravitational contraction of their increasing mass. The outflowing material on both sides of the accretion disk glows through the reflection of this starlight.

FIGURE 4.5



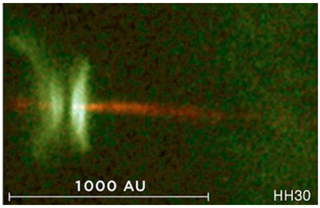
- The dense accretion phase continues until the dusty envelope begins to diminish. The bipolar outflows themselves carve cavities in the envelope and help break it up. At this point, the protostar itself is still slowly contracting and is typically called a T Tauri* star for the vast majority that have masses less than 2 solar masses.

- Such T Tauri stars continue their slow contraction for millions of years until their cores are hot and dense enough for hydrogen fusion to ignite and provide a long-lasting power source. The surrounding thick disk of gas and dust also continues to evolve over millions of years into a thinning protoplanetary disk.

- As the dusty envelope surrounding a T Tauri star and its disk fades away, many of these systems can become observable at optical or near-infrared wavelengths.

- Some of the most interesting cases exhibit narrow jets of outflowing gas. This Hubble optical image [FIGURE 4.6] reveals such a bipolar jet in an object known as HH 30. The jet is seen on both sides of an edge-on disk that blocks the direct view of the young T Tauri star driving this activity. Strong magnetic fields associated with the star and the disk are likely responsible for focusing the jet into a narrow beam that is visible over a length of 1000 AU. The clumpy nature of the gas in the jet indicates that this focused mass outflow is episodic in nature.

FIGURE 4.6



- HH 30 is an example of a Herbig-Haro object. Such objects are defined as patches of nebulosity associated with bipolar outflows from young stellar objects into the ambient interstellar medium. Although the most photogenic HH objects have well-collimated jets terminating in bow-shaped shock fronts, most have irregular morphologies.

HH objects are a telltale signature of the bipolar outflows that are a key step in the star formation process.

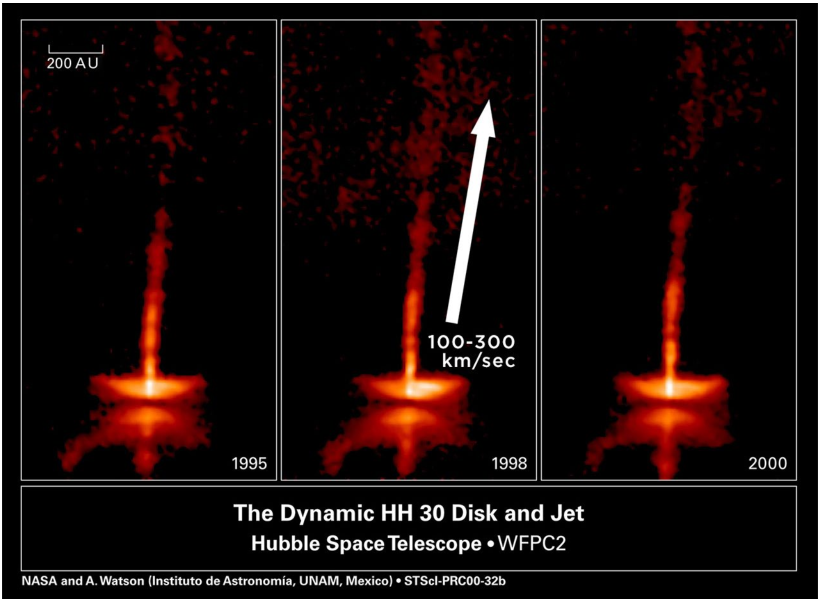
* This name comes from the well-studied prototype in the Taurus star constellation.

- Since the study of HH objects was pioneered in the 1940s, it has become clear that they are ubiquitous in star-forming regions, with more than 500 known to date. Their appearance can change on short timescales, especially when viewed at high spatial resolution with Hubble.

- Images from Hubble that track the motion of individual gas clumps in the HH 30 jet over the course of 5 years indicate that the clumps are moving away from the star at velocities ranging from 100 to 300 km/s [FIGURE 4.7]. This dynamic evolution is consistent with short lifetimes of about 10,000 years for a typical HH object. Coupling such short lifetimes with their ubiquity in molecular cloud regions indicates that HH objects are a common feature of star formation.

- Given their changeable nature and sharp features, HH objects have provided some of the most spectacular Hubble images of star formation at work in the Milky Way.

FIGURE 4.7



HH 24

- HH 24 is embedded in one of the dark nebulae above Orion's belt that is associated with the giant molecular cloud Orion B. As seen in this optical image centered on HH 24 and covering a sky area equivalent to 4 Moons [FIGURE 4.8], the region is threaded with multiple dark nebulae blocking the background starlight. The weak optical red emission associated with HH 24 indicates that its dust envelope is beginning to break up.

FIGURE 4.8

- However, it is in the near-infrared with Hubble that the jets of HH 24 really stand out. This image [FIGURE 4.9] spans about ¾ of a light-year at the 1500 light-year distance of HH 24. It is a sum of 5 exposures in 3 near-infrared colors spanning 2.5 hours of exposure time. The longest-wavelength near-infrared color is shown as red in this image, and the shortest is shown as blue. The overall color scheme is designed to best bring out the smallest-observable details in the structure of this HH object.

- On a large scale, the narrow bipolar jets of HH 24 are centered in an hourglass-shaped cavity in the dusty cloud envelope. The bottom jet extends for ½ a light-year through the bottom of the lower cavity. The size of the cavities tells us that the bipolar outflow has already cleared out much of the dust envelope in the vicinity of the jets. Yet the central dust cover is still too thick for Hubble's near-infrared view to directly reveal the young stellar object driving the jets of HH 24.

- Another jetlike cavity extends to the upper left from this central dusty region. The interior of this cavity shows other patchy HH objects driven by another hidden young star.

- The many knots in the structure of the HH 24 jets are due to blobs of infalling gas being blown out by the star at velocities of hundreds of km/s along the polar rotation axis. As these blobs catch up to and smash into other blobs ejected previously, they heat up and radiate light.

- The sharp collimation of these blobs in the bottom jet of HH 24 is truly remarkable. This jet has a thickness of less than 400 AU over the initial 12,000 AU of its length. It's not clear what keeps this gas flow so tightly aligned. The most likely candidate is a strong magnetic field woven into the dust-enshrouded central star and its accretion disk.

- Note that the knots in the upper jet are less aligned and more turbulent in appearance. It is possible that this jet is disturbed by the bipolar outflow from a star just to the right of the image center. Indeed, note the faint hourglass structure in the nebulosity centered on this star. The group of stars located just below this one may be producing other nearby HH features.

FIGURE 4.9

- The ubiquity of HH objects can be seen on a larger scale elsewhere in Orion. For example, this ground-based optical view of a region of the Orion A molecular cloud located about 2 Moon widths below the Orion Nebula covers a Moon-sized sky area [FIGURE 4.10]. It reveals a complex region of young stars, nebulae, and dozens of HH objects. Indeed, the region is so dense with HH objects that identifying the specific young stars responsible for them is not always clear.

FIGURE 4.10

- The large bow shock feature labeled HH 222 just to the upper right of the center of FIGURE 4.10 is also known as the Waterfall based on its appearance. The young star responsible for this Waterfall feature is actually associated with the nebula labeled NGC 1999 in the lower left of the image. It had a massive bipolar outflow event about 25,000 years ago that is now impacting the Waterfall gas and causing it to glow. The separation of 10 light-years between this star and the Waterfall shock makes it one of the largest HH outflows known.

READINGS

Bally and Reipurth, *The Birth of Stars and Planets.*
Beech, *The Pillars of Creation*.
Chambers and Mitton, *From Dust to Life*.
Hartquist, Dyson, and Ruffle, *Blowing Bubbles in the Cosmos*.

QUESTIONS

1. How do the orbital paths of the planets in the solar system support the standard model of star formation?

2. What would HH 24 look like if its most-sharply-collimated jet was pointed directly at Earth?

Lecture 5

A STAR CLUSTER BLOSSOMS: WESTERLUND 2

Typically, stars do not form in isolation. The most massive parent clouds can give birth to thousands of stars before their gas thins out within a few million years. Astronomers refer to such localized stellar families as star clusters. The youngest star clusters are often found close to their parent clouds. One of the best examples of such a newborn cluster is Westerlund 2. Located at a distance of 14,000 light-years in a rich star-forming region of the Carina constellation, this cluster is about 2 million years old and contains some of the hottest, most luminous stars in the galaxy.

Main-Sequence Stars

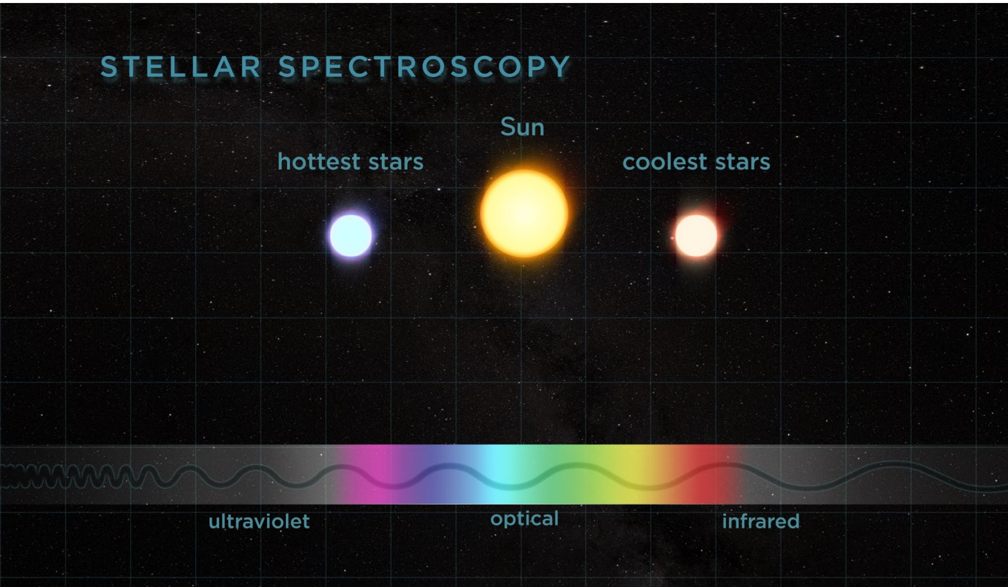
- The disk of the Milky Way contains thousands of star clusters, each consisting of dozens to thousands of stars. Since the stars in a cluster are all at about the same distance and all have about the same age, clusters provide a key laboratory to compare stellar properties.

> Some star clusters are bright enough to spot by eye or with binoculars.

- The science of stellar spectroscopy begins with measuring the brightnesses of stars as a function of wavelength in the same way that a glass prism can break up the white light of the Sun into its constituent colors. The hottest stars emit more shorter-wavelength blue light than red light. The coolest stars emit more longer-wavelength red light than blue light [FIGURE 5.1].

- A closer examination of a star's spectrum also reveals a lack of light at certain discrete wavelengths. Such so-called absorption lines are due to atoms and molecules in the star's atmosphere that absorb photons with these wavelengths. For example, the strong absorption line seen in the spectra of many stars at a red wavelength of 656 nanometers is due to hydrogen.

FIGURE 5.1



- Stellar spectra show different patterns of absorption lines that are related to a star's surface temperature and the composition of its atmosphere. The hottest stars follow an O-type pattern, with absorption lines from highly ionized atoms. The coolest stars follow an M-type pattern, with many molecular lines. In this way, a star's absorption-line pattern can be classified on an OBAFGKM spectral-type scale that reflects its surface temperature. In other words, the spectrum of a star tells us its temperature.

- Further patterns emerge when comparing the spectral types and luminosities of a number of stars, such as those in a star cluster. Astronomers Ejnar Hertzsprung and Henry Norris Russell pioneered such studies in the early 1900s.

- The stellar comparisons are typically made through a plot known today as a Hertzsprung-Russell (HR) diagram [FIGURE 5.2]. The *x*-axis of this diagram can be plotted in terms of stellar surface temperature or spectral type since both quantities are directly related.* The stellar luminosities plotted on the *y*-axis of the HR diagram are usually expressed in terms of the Sun's luminosity.

- In the HR diagram of a young star cluster, essentially all of the stars are found on a curved band across the diagram called the main sequence. Based on theoretical studies and a variety of observations, we know that stars spend most of their energy-producing lives on the main sequence. Specifically, main-sequence stars are powered by the nuclear fusion of hydrogen into helium in their cores. The highest-mass main-sequence stars have the highest surface temperatures and the highest luminosities.

- Based on a stellar census of young star clusters, such high-mass stars are rare. On average, star formation yields 1 star with a mass greater than 10 solar masses for every 260 stars with a mass less than this amount. The O-type main-sequence stars, which have masses greater than 15 solar masses, are the rarest by far. They are not only produced in small numbers, but they also have main-sequence lifetimes of only a few million years. The net result is that among the 300 billion stars in the Milky Way today, only about 30,000 are O-type main-sequence stars.

* The temperatures of stars are typically expressed on the Kelvin scale, where degrees Kelvin is equal to degrees Celsius plus 273°. On this scale, water freezes at 273 K and humans normally have a body temperature of 310 K.

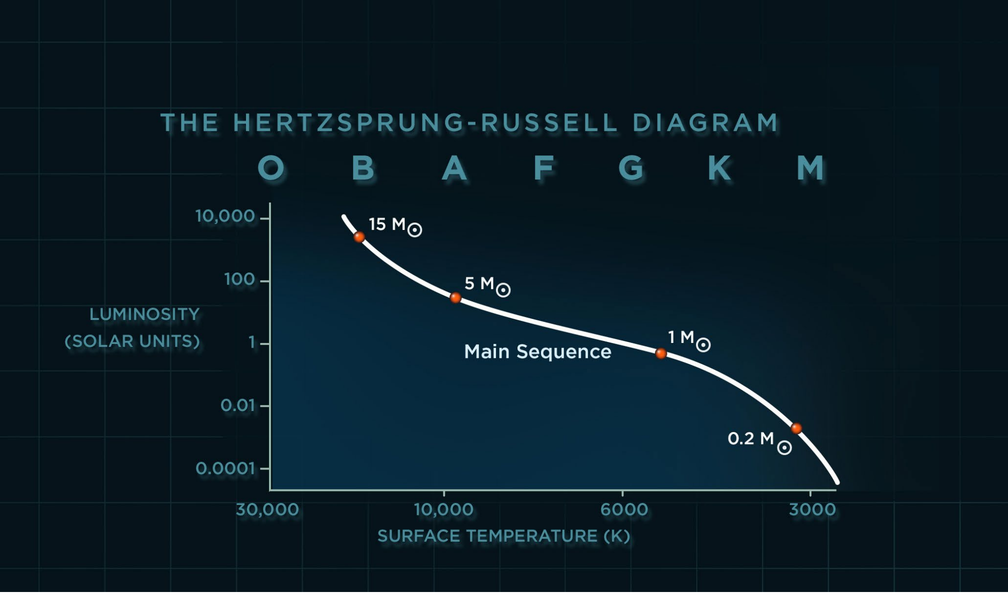


FIGURE 5.2

- After a star completes its main-sequence lifetime, burning hydrogen into helium in its core, its evolution proceeds in one of 2 directions, depending on its mass:

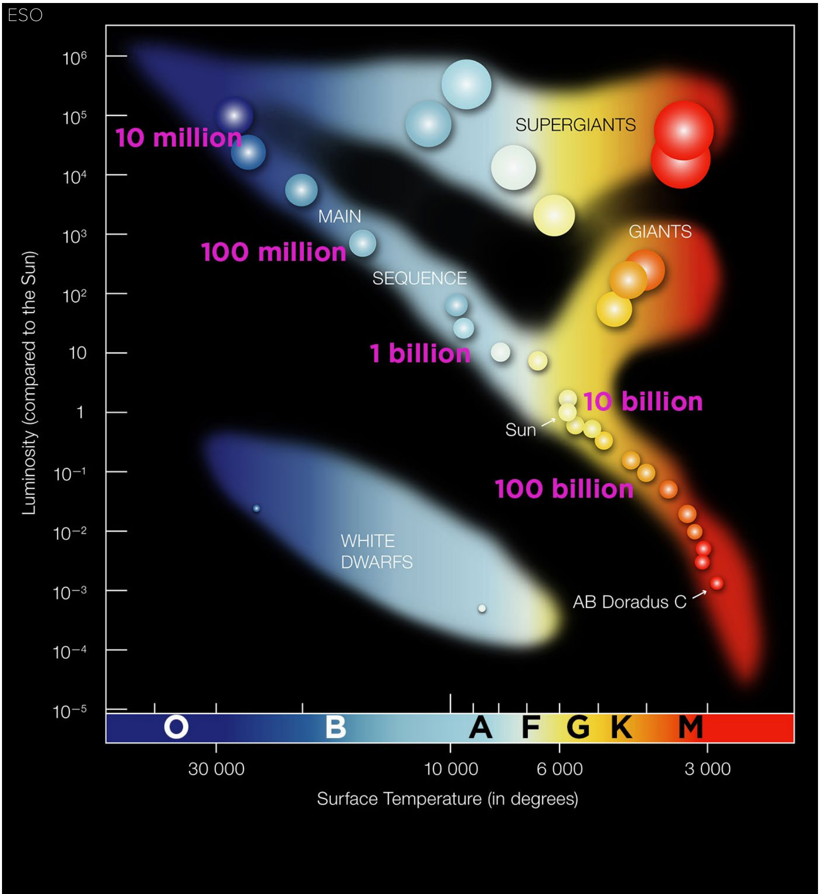
  - If the star has a mass greater than 8 times that of the Sun, it becomes a cooler, more luminous supergiant star. Such a star's typical size is equal to the orbit of Mars around the Sun. After the supergiant shines for about 10% of its main-sequence lifetime, it explodes as a supernova. At the center of this explosion, the supernova leaves behind a dense, city-size neutron star or a black hole. About 1% of all Milky Way main-sequence stars, including the hotter B types and all of the O types, evolve in this manner.

  - The other 99% that have masses less than 8 solar masses become a cooler, more luminous red giant star when their cores run out of hydrogen. A red giant has a typical size comparable to Earth's orbit around the Sun. It lasts about 10% as long as its main-sequence progenitor before mildly blowing off its outer layers. This so-called planetary nebula stage lasts for about 50,000 years and exposes the stellar core. The resulting white dwarf star is hotter but much less luminous than its main-sequence parent. It is a dense, Earth-size object that is no longer producing energy through nuclear fusion and slowly cools off over billions of years.

- Up to ages of a million years or so, all of the stars are on the main sequence. After this time, the hottest O stars will start moving off the main sequence to the cooler, luminous supergiant region of the HR diagram. The cluster will thus begin to show some red stars that rival the O stars in luminosity. By the time the cluster reaches an age of about 10 million years, it no longer has any O-type main-sequence stars left.

- At an age of 500 million years, all of the B-type main-sequence stars are gone, too, and red giants have begun to appear in a cooler, luminous region of the HR diagram below the supergiants. As the main sequence of the cluster continues to shorten with time, white dwarfs begin to appear in a hotter, less luminous region of the HR diagram [FIGURE 5.3].

FIGURE 5.3



- Thus, the pattern of a cluster's HR diagram changes with time [FIGURE 5.4]. The key diagnostic is the so-called turnoff point of the cluster's main sequence. This point on the HR diagram corresponds to the hottest main-sequence stars present in the cluster. Astronomers can thus determine a star cluster's age by using its HR diagram to measure this turnoff point.

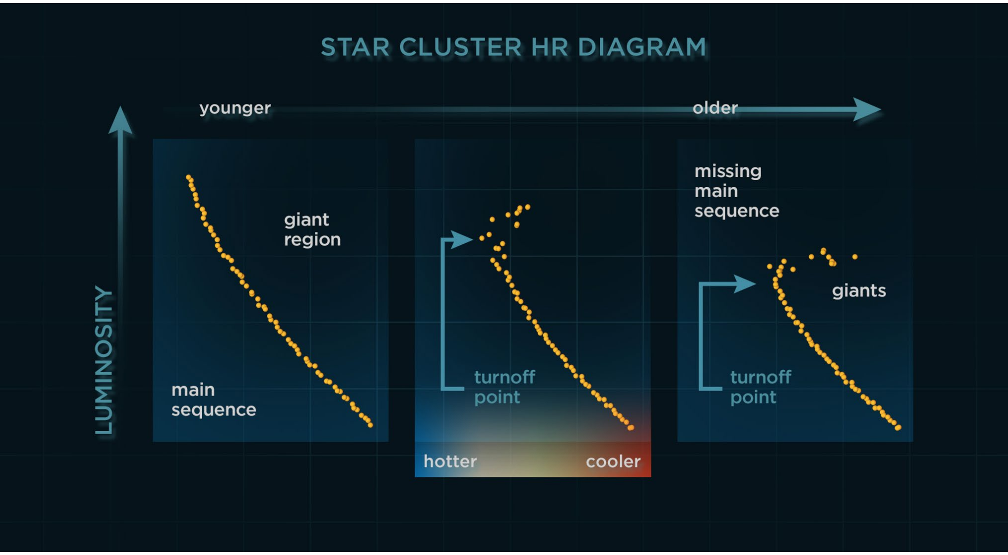


FIGURE 5.4

The Westerlund 2 Star Cluster

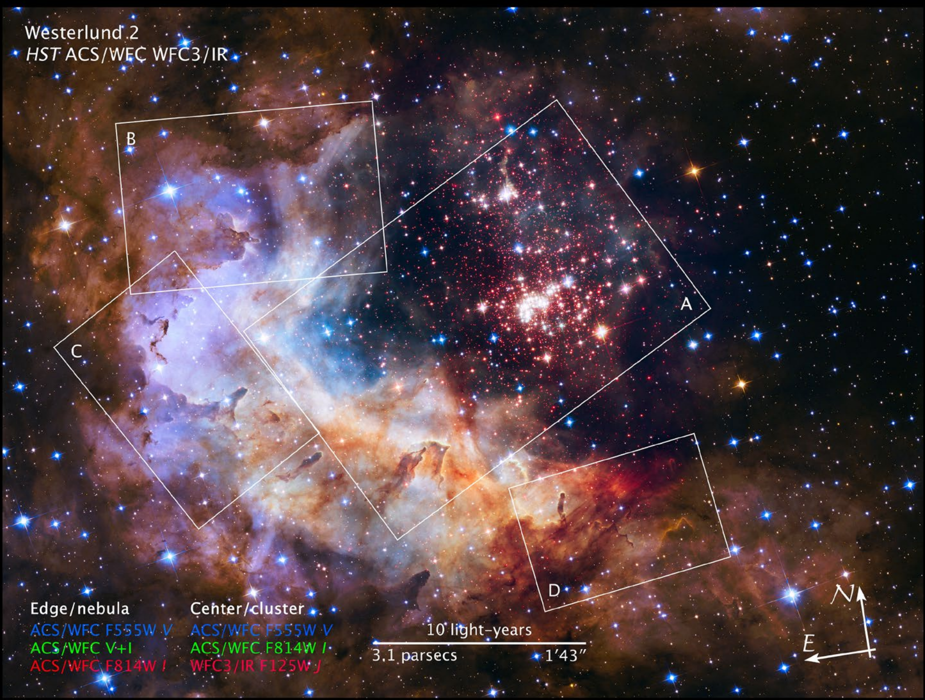
- There are only a few star clusters that are as massive and luminous as Westerlund 2† in the entire Milky Way. This star cluster is surrounded by a giant molecular cloud spanning dozens of light-years with a total mass that's more than 100,000 times that of the Sun.

† Westerlund 2 was identified by the Swedish astronomer Bengt Westerlund in 1961.

- As shown in this Hubble view of Westerlund 2, the intense ultraviolet radiation and strong stellar winds of the hot stars in the cluster are illuminating and sculpting the nebular surface of its nearby parent cloud. Although few in number, each of these hot stars is about a million times more luminous than the Sun.

- The Hubble image shows dust pillars arising from the illuminated cloud surface. The surrounding nebula glows due to the intense ultraviolet radiation from the hottest cluster stars. The dust structures are light-years in size and point in the direction of the cluster. Their exteriors are being sculpted by the radiation and strong winds of the hot cluster stars.

FIGURE 5.5



- This view of Westerlund 2 is a mosaic of multiple optical and near-infrared images obtained with its Advanced Camera for Surveys and the Wide Field Camera 3. The combined image is a sum of 72 exposures spanning a total of 6.4 hours of observing time. The image covers a sky area that's equivalent to 6% that of the Moon. At the 14,000-light-year distance of Westerlund 2, the image spans 30 light-years. The cluster itself is about 7 light-years across and 3 light-years distant from the nebula at its nearest point.

- Like the Horsehead Nebula, one of the largest dust pillars in the nebula is built off of its dark cloud base on the lower left of the image. Its dense concentration of dust and gas has survived erosion by the star cluster radiation and winds longer than its less dense surroundings. The many faint red points of light in the nebula are mostly protostars emerging from the dust. The brighter bluish stars are mostly foreground to the nebula.

- Based on the Hubble image, we know that the stellar surface density in Westerlund 2's dense core is at least 100 stars per square light-year! Due to interstellar reddening by the foreground dust, all of the stars in the cluster have colors ranging from white to red. The few blue stars seen are all in front of this dust screen and are not cluster members.

- The HR diagram for the 3000 stars in the cluster yields an age of about 2 million years. In other words, the cluster is young enough for essentially all of its O stars to still be on the main sequence. Among these stars, the hottest few are each 50 times more massive than the Sun. Such stars have strong winds of charged particles that flow outward at speeds up to 4 million miles per hour!

- These massive winds have been primarily responsible for clearing out the region between the Westerlund 2 cluster and its parent cloud to date. Within a million years or so, the next phase will commence, as the O stars start exploding as supernovas. Each supernova explosion ejects about 10 solar masses of gas at velocities up to 10% that of light.

- These explosions will complete the separation of the star cluster from its parent cloud. They will also lessen the gravitational mass holding the cluster together. As Westerlund 2 continues its orbital journey around the Milky Way, the cluster will slowly disperse over time as it encounters the gravitational fields of other stars and gas clouds.

The Future of Young Massive Star Clusters

- What does the future hold for Westerlund 2 and other young massive star clusters? Interestingly, it is quite likely that the Sun formed in such a cluster some 4.6 billion years ago.

- On the night sky of a very young Earth, there would have been hundreds of stars far brighter than any in our current sky amid brilliant nebulae with colors easily apparent to the naked eye. Indeed, compared to this striking foreground, the Milky Way itself would have been hardly noticeable on the sky.

- At that time, the nearest star to the Sun was likely less than 1/10 of a light-year away, compared to the current value of 4.3 light-years. After a few million years, the most massive stars in the Sun's cluster would have rapidly evolved, exploded as supernovas, and blown away the nebular remnants of the cluster's parent cloud.

- As the solar cluster orbited the center of the Milky Way at its distance of 27,000 light-years, gravitational interactions with other stars and gas clouds in the galactic disk would have slowly spread out the stars in the cluster. After about 200 million years, the Sun likely separated from its stellar sisters and brothers.

- Since that time, the Sun has made twenty 230-million-year orbits around the galaxy alone. Its original cluster siblings are now spread out over thousands of light-years. Most star clusters in the disk of the Milky Way break up during their first few hundred million years; only a few survive billions of years. In other words, most of the stars in the galactic disk are former cluster members.

- The disk orbits of Westerlund 2 and other young clusters are similar to that of the Sun in being far from the galactic center. It is likely that some of these clusters will also dissipate within a few hundred million years. However, it is possible that Westerlund 1‡—the most massive young star cluster in the galaxy—may be massive and dense enough to survive much longer.

‡ Westerlund 1 is located about 13,000 light-years away in the star constellation Ara. This star cluster is about 8 light-years across and contains thousands of stars, with a total stellar mass that is 50,000 times greater than that of the Sun and 5 times greater than that of the Westerlund 2 cluster.

- In the case of the Sun, all of its high-mass brothers and sisters would now be long dead. However, astronomers continue to spectroscopically search for its long-lost solar-type siblings among the many billions of stars in the Milky Way. They have recently succeeded in finding a few candidates with the same age and elemental composition as the Sun hundreds of light-years away.

> The Sun is a G star that has already lived for 4.6 billion years of its 10-billion-year main-sequence lifetime.

READINGS

Portegies Zwart, "The Long-Lost Siblings of the Sun."
Portegies Zwart, McMillan, and Gieles, "Young Massive Star Clusters."
Stevenson, *The Complex Lives of Star Clusters.*
Weintraub, *How Old Is the Universe?*

QUESTIONS

1. Among the O-type and G-type main-sequence stars in the galactic disk today, which type has a higher fraction of its stars gravitationally bound in star clusters?

2. How would the appearance of Westerlund 2 and its environment be different today if it had been born with no O-type or B-type stars?

Lecture 6

AN INTERSTELLAR CAVITY: THE BUBBLE NEBULA

Over the course of their lives, all stars lose mass at various rates through stellar winds and, occasionally, explosions. Depending on a variety of factors, ranging from the strength and symmetry of these outflows to the homogeneity of their local environment, they can produce spherical structures in the surrounding interstellar medium. Such interstellar bubbles can range in size from much less than 1 light-year to much more than 100 light-years across. The Bubble Nebula, located in the galactic disk at a distance of 8800 light-years toward the star constellation Cassiopeia, is perhaps the most distinctive of these globular interstellar features.

Stellar Winds and Mass Loss

- During its 10 billion years on the main sequence, the Sun's mass loss has been and will continue to be quite low. It has lost only 0.01% of its mass over the past 4.6 billion years, which works out to an average mass-loss rate of 1 Earth mass every 150 million years.

- This mass loss is driven by the solar wind emanating from the Sun's outer atmosphere, known as the corona. Relative to the bright disk of the Sun, the corona is very faint. It is only visible to the naked eye during the few minutes of a solar eclipse when the Sun's disk is completely covered by the Moon.

- The solar corona has a temperature of 2 million degrees Kelvin and a density that is just one-trillionth that of the Sun's surface. The corona's hot, tenuous gas is an ionized plasma of mostly electrons and protons. It is heated by activity associated with the Sun's magnetic field, such as sunspots and solar flares. Due to this heating, a wind of coronal plasma continually escapes the Sun at a velocity greater than the speed of sound. At the 1-AU distance of the Earth from the Sun, the solar wind has been measured to reach a speed of 750 km/s.

- This high-velocity wind slows to subsonic speeds when it begins to interact with the denser gas in the local interstellar medium. Similar to the flow of water around a source in a sink, this turbulent interaction region is known as a termination shock. In the case of the solar system, it is located at a distance of about 90 AU from the Sun.

- A bit farther out is the so-called heliopause, where the solar-wind pressure has declined to the point where it equals the pressure of the local interstellar medium.* The solar-wind bubble produced by the Sun currently has a radius of only 0.002 of a light-year.

* Launched in the 1970s, the Voyager 1 and Voyager 2 space probes respectively crossed this threshold in 2012 and 2018 at a measured distance of 120 AU from the Sun.

- In about 5 billion years, the Sun will leave the main sequence as its core runs out of the hydrogen necessary to power its nuclear fusion into helium. As this now-helium core begins to slowly contract and heat up due to gravity, it will ignite hydrogen fusion in the hydrogen-rich region around the core. This hydrogen-shell burning will produce much more energy.

- In response, the Sun will increase in size by a factor of 200 and become a red giant star with a surface temperature that has cooled by a factor of 2000 to 3000 Kelvin. The outer atmosphere of such a huge star is cool enough for small solid dust grains to condense out of the gas. The star's gravitational hold on its bloated outer atmosphere is weak enough that the star's radiation pressure on these grains can push them into a slow wind that escapes the red giant with a speed up to 30 km/s. The resulting mass loss drives these grains of stardust along with some gas into the interstellar medium.

- As a red giant, the Sun will lose about 1 Earth mass every 300 years due to this process. Such a mass-loss rate is 500,000 times faster than when the Sun is on the main sequence. Overall, during its billion years as a red giant, the Sun will lose about 50% of its mass.

- Near the end of its red giant life, nuclear fusion will have left the Sun's interior with a mostly carbon core the size of the Earth surrounded by a helium-fusion shell and a hydrogen-fusion shell. The helium-burning shell can have extreme fluctuations in its energy release. These fluctuations drive episodic thermal pulses that will eventually blow off the Sun's outer envelope over thousands of years. During this time, the Sun will lose mass at an average rate of about 1 Earth mass every month.

- Such mass-loss pulses in a red giant star will eventually separate its gaseous envelope from the core. The ultraviolet light from this hot, exposed core ionizes the gas in the final expanding shells. Such objects are known as planetary nebulae,† despite the fact that they have nothing to do with planets.

- The planetary nebulae mark the evolutionary transition from a red giant to a white dwarf star. Since the gaseous envelopes of these nebulae are expanding away at a typical velocity of 25 km/s, their lifetimes are only about 50,000 years.

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† *Planetary nebulae* is an old term based on initial observations long ago where they looked like planetary disks in a small telescope.

The fact that more than 3000 planetary nebulae have been identified in the Milky Way to date despite this short lifetime shows that they are a common stage in the late evolution of low-mass stars like the Sun.

- Since the lower-mass stars that produce planetary nebulae are billions of years old, these nebulae are typically not associated with star-forming regions or dense interstellar clouds. Consequently, their gas bubbles are usually expanding in low-density regions of the interstellar medium.

- To obtain a more complete structural understanding of planetary nebulae, Hubble has imaged many of them in great detail. They show a variety of structures and symmetries, ranging from spherical to bipolar. These variations are typically independent of the surrounding interstellar medium in which they are expanding.

- Collectively, the Hubble images illustrate that the planetary nebula transition from a red giant to a white dwarf is quite complex, with multiple mass-loss episodes of varying character. Indeed, only about 20% of all planetary nebulae appear to exhibit true spherical symmetry.

The Bubble Nebula

- In the case of the hottest, most massive stars, their intense radiation drives stellar winds that produce mass-loss rates that are typically a billion times greater than that of low-mass main-sequence stars.

- With a surface temperature of 38,000 K and a mass that is 45 times that of the Sun, the star BD +60°2522 is an excellent example of such an object. It is an O-type star that is a few million years old and is still located near the dense interstellar cloud complex from which it was born. With a stellar wind of 2000 km/s, it is currently losing mass at a rate of 1 Earth mass every 3 years.

- For tens of thousands of years, this wind has been inflating an interstellar bubble around the star that is now 8 light-years across. The Hubble view of this Bubble Nebula [FIGURE 6.1] is a mosaic of 36 exposures spanning 7.7 hours of observing time. The colors reflect the nebular brightness at key wavelengths sensitive to the emission from atoms and ions of different elements. Specifically, the light from doubly ionized oxygen is blue, atomic hydrogen is green, and ionized nitrogen is red. The brightness of each color reflects the physical conditions in the nebula and the abundances of these ions and atoms.

FIGURE 6.1

- The edge of the bubble is expanding into the surrounding interstellar medium at a velocity of 25 km/s. The wind of the O star is thus acting like a giant snowplow, sweeping up the surrounding interstellar gas. The resulting total mass in the swept-up shell of the Bubble Nebula is about 10 times that of the Sun.

- Extending to the upper right of the mass-losing O star in this Hubble close-up [FIGURE 6.2], the bubble edge is interacting with dense knots of gas and dust about 1 light-year away from the star. These knots form the top of a brownish-orange exterior dust pillar like the Horsehead Nebula. The intense ultraviolet light from the O star is evaporating material off of the topmost dust feature. This evaporative flow is pushing back on the windblown bubble like a finger on a balloon. The blue loops of ionized oxygen emission between the star and the top of the dust pillar reflect the turbulent 3-dimensional interaction between these gas flows.

FIGURE 6.2

- On a larger scale, the Bubble Nebula appears to be nested in a bigger bubble. This ground-based image [FIGURE 6.3] is 50 light-years across at the 8800-light-year distance of the nebula. The partial shell of glowing gas around the Bubble looks very similar to the nebula surrounding the Westerlund 2 star cluster.

FIGURE 6.3

- The Bubble Nebula's O star is both inflating the interstellar bubble with its strong wind and ionizing the surrounding gas beyond with its intense ultraviolet radiation. This demonstrates how just a single O star can impact its interstellar environment.

- Near the end of its evolution, a massive O star typically goes through a short-lived phase of about 100,000 years where its mass-loss rate can increase further by a factor of 10. Such an object is called a Wolf-Rayet star. Its extreme mass loss can produce a surrounding nebula illuminated by the star's ultraviolet light. Some of these Wolf-Rayet nebulae have a bubble-like symmetry.

Superbubbles

- When a massive star is no longer able to produce energy through nuclear fusion, its core gravitationally collapses from something the size of the Earth to something the size of a city in less than a second. This collapse leads to a shock wave that blows away the rest of the star in a massive explosion called a supernova. This mass-loss pulse of several solar masses expands into the surrounding interstellar medium at velocities up to 30,000 km/s, which is 10% of the speed of light.

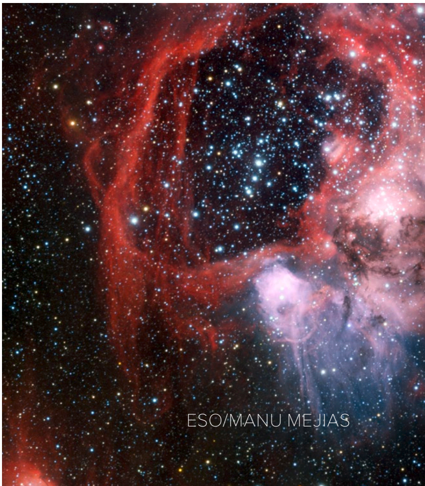
- The occurrence of multiple such supernovas in the early life of a young massive star cluster can produce a so-called superbubble in the surrounding region. These superbubbles are typically hundreds of light-years in size and thus much larger than the Bubble Nebula.

- Such large interstellar features are easiest to image optically in nearby galaxies like the Large Magellanic Cloud (LMC). It is a satellite galaxy of the Milky Way located in the Dorado star constellation at a distance of 160,000 light-years. The LMC is an irregular dwarf galaxy that is 1⁄7 the size of the Milky Way and has about 1% of its mass. And it has lots of interstellar matter and ongoing star formation.

- Among the interstellar superbubbles in the LMC, one of the most optically prominent is known as N44. As shown in this ground-based optical image [FIGURE 6.4], the red hydrogen nebulosity outlines the exterior of the superbubble. It measures about 250 light-years across, with the young star cluster NGC 1929 in its interior. Over the past million years or so, a few of the most massive stars in this cluster have exploded as supernovas.

- There are a number of superbubbles in the gas-rich disk of the Milky Way. Due to the dust obscuring distant optical observations in the disk, most have been identified through the radio emission of the hydrogen atoms in their dense gas shells. The nearest superbubbles cover large regions of the sky.

FIGURE 6.4



ESO/MANU MEJIAS

- A good example is the Orion-Eridanus superbubble,‡ which actually stretches across several star constellations on the sky. Hubble captured this deep image of the active star-forming regions in Orion [FIGURE 6.5] (this image was featured in lecture 3 [FIGURE 3.2]). Massive stars have been exploding as supernovas amid these nebulae and molecular clouds for millions of years. These explosions have opened up a superbubble that stretches more than 1000 light-years in its longest dimension. One edge of this huge gas cavity lies near the prominent nebular arc of Barnard's Loop. This 300-light-year-diameter gas feature was swept up by a supernova about 2 million years ago.

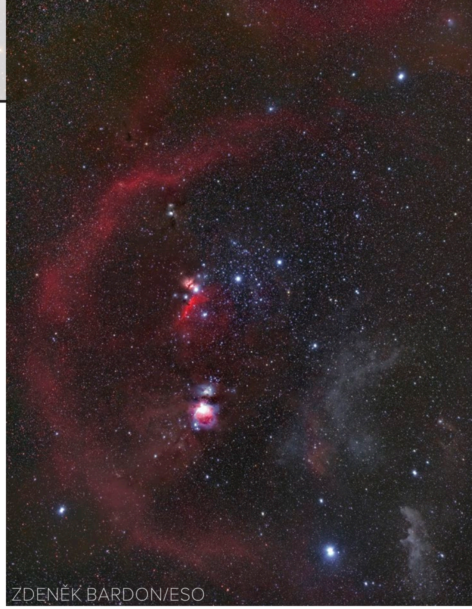

ZDENĚK BARDON/ESO

FIGURE 6.5

- Our Sun is located inside another superbubble called the Local Bubble. As shown in FIGURE 6.6, it is somewhat oblong in shape, with its longest axis stretching about 500 light-years toward the bright star Beta Canis Majoris. The other superbubble shown adjacent to the Local Bubble encompasses the bright supergiant star Antares. Surrounding these 2 large interstellar cavities are other superbubbles like Orion-Eridanus and a number of dense molecular clouds.

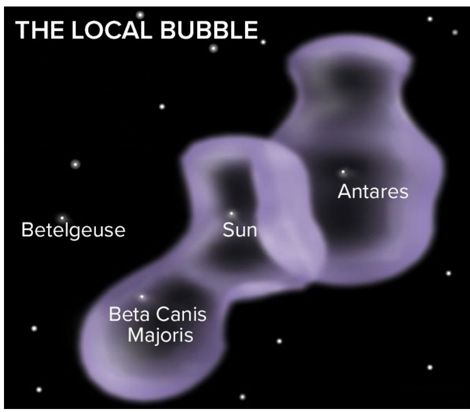


FIGURE 6.6

‡ The Orion-Eridanus superbubble is expanding at a velocity of about 15 km/s, and its nearest edge is located at a distance of 500 light-years from the Sun.

- Compared to the molecular clouds, which can have gas densities as high as a million atoms per cubic centimeter, the Local Bubble has a density of just 0.01 atoms per cubic centimeter. Inside this Local Bubble of hot, tenuous gas, there are smaller, cooler clouds with densities of about 0.1 atoms per cubic centimeter. The Sun is currently passing through one of these clouds after entering the Local Bubble[§] millions of years ago. As the Sun orbits the Milky Way, it has traversed—and will continue to traverse—a variety of interstellar environments.

- During its long journey, the solar system must have traveled through dark clouds and superbubbles multiple times, with the surrounding interstellar gas densities and temperatures varying by factors up to a million or more. Indeed, there must have been a time long ago when the night skies on Earth were completely devoid of stars due to a surrounding dark cloud. Fortunately, humanity has come of age at a time when our current location inside the Local Bubble provides an excellent view of the Milky Way!

READINGS

Branch and Wheeler, *Supernova Explosions.*
Frisch, "The Galactic Environment of the Sun."
Hartquist, Dyson, and Ruffle, *Blowing Bubbles in the Cosmos.*
Zimmerman, "Spider Webs in Space."

QUESTIONS

1. Given the similarities in appearance, how is it possible to determine that the Bubble Nebula is not a planetary nebula?

2. Why are superbubbles typically less symmetric than the Bubble Nebula?

§ The Local Bubble was produced by multiple supernova explosions about 10 million years ago.

Lecture 7

THE INTERSTELLAR ECHO OF A VARIABLE STAR

A star's luminosity can vary significantly over the course of its life.* In particular, as massive stars evolve into giants and supergiants, they typically pass through a short-lived phase where they oscillate in luminosity due to pulsations in their size and surface temperature. Such stars are known as Cepheid variables. They are especially important in astronomy because a tight correlation exists between their pulsation periods and average luminosities. This correlation makes them an exceptional cosmic yardstick for determining the distances to other galaxies beyond the Milky Way.

* Fortunately for us, the light output of a middle-aged main-sequence star like the Sun is remarkably constant over timescales of many millions of years. However, some stars regularly vary in brightness by a factor of 2 or more on timescales as short as a few days.

Reflections and Light Echoes

- With at least 6 stars visible to the naked eye as a tight group, the Pleiades [FIGURE 7.1] is the brightest and most recognizable star cluster on the sky. It is located in the constellation Taurus at a relatively nearby distance of 440 light-years.

- Based on the colors and luminosities of its thousand stars, the Pleiades cluster is about 100 million years old. This age is well past the time that the cluster would still be associated with its parent cloud.

- Nevertheless, viewed up close, the Pleiades exhibits extended nebulosity around its brightest blue stars. The most likely explanation for these reflection nebulae is that they are being produced as the cluster passes through an unrelated, thin dust cloud. As the starlight from the brightest stars hits dust grains near them, some of that light is scattered in our direction. If the dust grains weren't there, we wouldn't see any nebulosity around the stars.

FIGURE 7.1

- In the case of the Pleiades, the brightness of the reflection nebulosity at any point is a function of both the luminosity and distance of the nearest stars. Specifically, the brightest dust is typically within 1 light-year of the brightest stars.

- The color of the Pleiades nebulosity appears blue because its brightest stars are bluish B-type stars and because interstellar dust grains reflect blue light more efficiently than red light. The reason for this color dependence in dust scattering is that the shorter wavelengths of blue light are closer in size to the average dust grain diameter.

- Given the distance of the dust from the stars in the Pleiades, its nebular light is typically a year or so older than the nearest starlight. Since none of the bright blue stars in the cluster are currently varying in brightness, the nebular glow is essentially constant over time.

- But what would it look like if there were a variable star in such a dusty environment and it quickly became much brighter?

- Fortunately, nature has given us a great example to study with Hubble [FIGURE 7.2]. It involves a faint star at a distance of 20,000 light-years in the constellation Monoceros, which is located near Orion on the sky. In January 2002, this star suddenly brightened by a factor of about 3000. For a short time, it was one of the most luminous stars in the Milky Way.

FIGURE 7.2

- As the 838th variable star found to that date in its constellation, it was given the name V838 Monocerotis (V838 Mon). From Hubble images of V838 Mon taken from 2002 to 2006, the star appears to be surrounded by a rapidly expanding debris shell produced by a massive explosion. But the apparent nebula expansion around V838 Mon is actually a light echo of a single stellar outburst reflected off of surrounding dust grains at different locations and distances.

- Prior to the burst, the star's light was far too faint to illuminate any of this dust. The light that reached us first was from the outburst of V838 Mon itself. This initial burst was followed by light echoes from dust at increasing total distance behind and in front of the star. The echoes got fainter and fainter with time and distance; they essentially faded out a decade after the initial burst.

- There is still no clear explanation for the outburst of V838 Mon, but it may be associated with the star expanding into a supergiant. It is possible that the dust surrounding the star has been shaped by previous mass-loss episodes.

The Pulsations of RS Puppis

- Among the thousand Cepheids currently known in the galaxy, RS Puppis is one of the most luminous. Its optical brightness varies by a factor of 3 over a pulsation period of 41 days. Located at a distance of 5600 light-years in the southern constellation Puppis, this Cepheid is unique because of its close proximity to a surrounding interstellar dust cloud.

- As viewed with Hubble, the intricate small-scale structure of this cloud is illuminated as its dust grains reflect the bright nearby light of RS Puppis. Furthermore, as the star pulsates in brightness, the nebular dust at different distances from the star reflects these variations. In scientific terms, this reflection nebula around RS Puppis exhibits a light echo.

- Instead of constant illumination like the Pleiades or a single burst of extremely bright illumination like V838 Mon, the reflection nebula around RS Puppis (RS Pup) is pulsing. Every 41 days, the input luminosity regularly varies between 14,000 and 30,000 Suns. Since the nebula is light-years in size, the light echoes of these pulsations ripple across its structure like waves on an ocean.

- The Hubble observations of RS Pup have 2 components:
    - The first is a multicolor image centered on the star and taken at a time when this Cepheid variable was near its lowest luminosity [FIGURE 7.3]. The sky area covered in the image equals about 1% that of the Moon. At the distance of RS Pup, this Hubble image measures 7 light-years across, with a resolution that can reveal solar system–sized features in the reflection nebula that are as small as 100 AU. It is a sum of 4 separate exposures spanning a total of 35 minutes of observing time. These 4 exposures include 2 each taken with blue and red color filters. The final summed image is displayed in 3 colors, with blue and red reflecting the nebular brightness in their respective filters and green added to reflect the brightness of the combined light in the 2 filters. The resulting appearance of the reflection nebula is a combined function of the dust location and structure plus the varying light echoes. The echoes of RS Pup at maximum light can be distinguished as the partial blue rings in the nebula. The bluish color is due to the hotter temperature of the star when it is brightest. The rings are incomplete because the dust distribution is not symmetric around the star. Overall, most of the nebular light appears to come from a thin dust screen in front of RS Pup.

FIGURE 7.3

☽ The second component of the Hubble observations involves 7 images taken at equally spaced times across most of the 41-day pulsation period of RS Pup [SEE THE VIDEO LECTURE]. The images were taken with a filter that isolated the polarized red light reflected by the nebula. Such imaging is especially sensitive to light scattered by dust grains. Since Hubble has a reduced field of view for this type of imaging, the polarized images are focused on the nebular region with some of the brightest scattering. The time between succeeding brightness peaks at any point in the nebula is equal to the 41-day pulsation period of RS Pup. Thus, every point in the reflection nebula will exhibit essentially the same light curve over time as this pulsating star [FIGURE 7.4]. However, each of these light curves is delayed relative to the star due to the longer light path followed by their respective light echoes. The light curves at different points in the nebula will be synchronized in time if their light paths to Hubble are the same length or differ by an integer factor of 41 light-days. Consequently, the entire nebula doesn't pulse in unison with RS Pup but has ringlike echoes around it.†

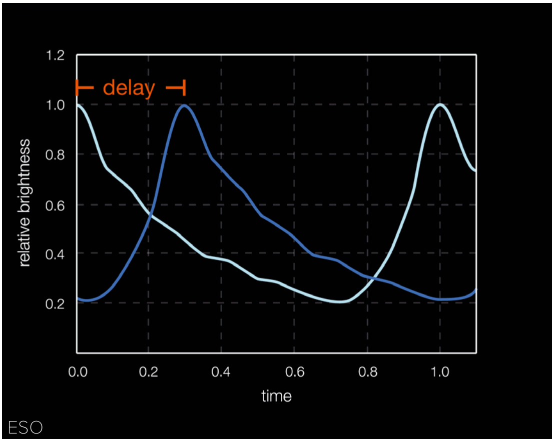


FIGURE 7.4

- The key phenomenon driving the pulsating light echoes around RS Pup is the star itself. It is a supergiant star with a mass of about 10 solar masses. Why does it pulsate in luminosity?

† Based on the amount of dust, RS Pup's reflection nebula must have a mass of about 300 solar masses. This amount of mass is far too much to have been lost by RS Pup over its evolution to date. Thus, the nebula must either be a remnant of its parent cloud or, more likely, a chance encounter of this Cepheid variable star with an interstellar cloud.

- In its comparison of stellar luminosities and surface temperatures, the Hertzsprung-Russell (HR) diagram [FIGURE 7.5] shows that stars can basically be categorized into 4 groups: main-sequence stars, red giants, supergiants, and white dwarfs. A star spends most of its life on the main sequence, fusing hydrogen into helium in its core.

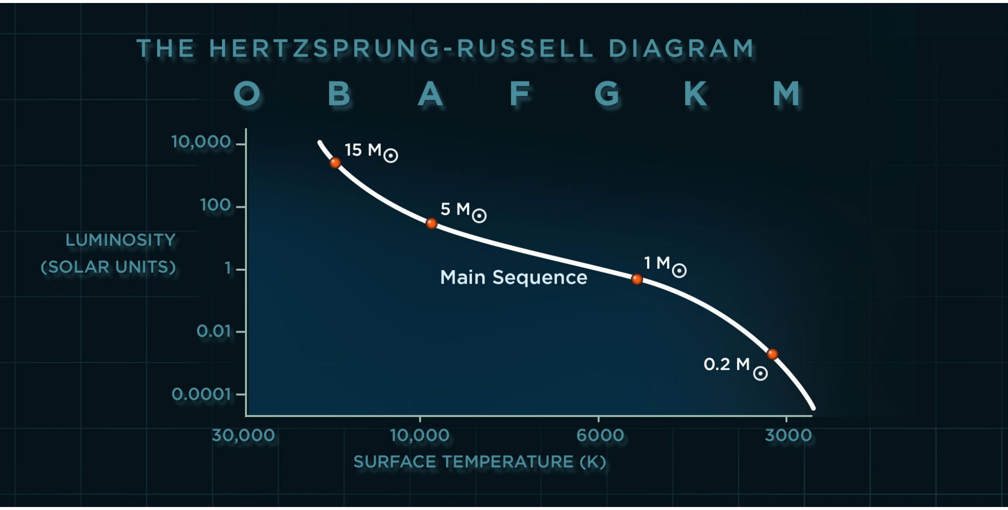


FIGURE 7.5

- With this essentially constant energy source, main-sequence stars are said to be in hydrostatic equilibrium. This equilibrium means that the radiation pressure trying to expand the star's gaseous envelope is balanced by the gravitational force of the star's mass trying to contract the envelope. The net result is that the size, temperature, and luminosity of a main-sequence star remains essentially constant for most of its life.

- When a massive star evolves off the main sequence, it becomes a cooler and more luminous supergiant. During this time, the star will pass through the so-called instability strip on the HR diagram. In this region of stellar luminosity and surface temperature, the hydrostatic equilibrium of a star can break down.

- Specifically, the problem begins when the outer layer of a supergiant star becomes hot enough to doubly ionize its helium and remove the electrons from these atoms. These freed electrons scatter and trap more of the outgoing radiation in the star's outer layer. As a result, the radiation pressure in this layer increases enough to overcome gravity and inflate the star.

- The inflation is short-lived, however, because the expansion increases the transparency of the outer layer and allows the trapped radiation to more easily escape. The expanded layer now cools, and gravity can overcome its reduced pressure. The star thus contracts back to its original size, and the cycle begins again.

- Note that during this pulsation cycle, the fusion energy production inside the star is constant. It is the changes in the transparency of its outer layer that drive the pulsation of the supergiant. As the star pulsates, its surface temperature is hottest and appears bluest at minimum size and is coolest and appears reddest at maximum size.

- In the case of RS Pup, its surface temperature peaks near 5900 Kelvin when its radius is 160 times that of the Sun. Its temperature cools to about 4600 Kelvin when it expands to a size that is 210 times that of the Sun. Thus, the spectral type of RS Pup effectively oscillates between that of an F-type and a G-type supergiant on the HR diagram's instability strip.‡

- The luminosity of RS Pup, like all stars, is proportional to the square of its radius times its surface temperature to the fourth power. The star is dimmest when it is at its smallest size during the 41-day pulsation cycle. The star is brightest after it quickly expands to its maximum size, followed by a slower decline back to its minimum.

The Period-Luminosity Relation

- A key relation exists between the intrinsic luminosity of a star, its apparent brightness on the sky, and the distance to the star. Specifically, the brightness of a star equals its luminosity divided by 4π times the square of the star's distance. In other words, the brightness of a star decreases in proportion to its distance squared.

‡ Massive stars spend only a very short part of their lives on the HR diagram's instability strip. Like most Cepheid variable stars, RS Pup will be pulsating for only a few tens of thousands of years.

- In practice, the apparent brightness of a star is relatively easy to measure well with an appropriate telescope and modern instrumentation. Its distance and intrinsic luminosity are typically much harder to determine, but one can be calculated if the other is known and the brightness has been measured.

- The importance of Cepheid variables to this distance issue is that their luminosity can be accurately determined based on measurements of their pulsation periods.

- Harvard astronomer Henrietta Leavitt discovered this Cepheid period-luminosity relation in the early 1900s. She focused her work on a group of 25 bright Cepheid variables found in the Small Magellanic Cloud (SMC). Since the 25 Cepheids were all part of the same cluster that was very far away, the distances to each of the Cepheids had to be essentially the same. Consequently, any brightness differences among these Cepheids had to be due to differences in their luminosities.

- Leavitt found that the SMC Cepheids with longer pulsation periods had larger average luminosities than those with shorter periods. This Cepheid period-luminosity relation became a key tool to derive the distance to any star group with Cepheid variables whose luminosities could thus be inferred by simply measuring their pulsation periods.[§] Today's best measurements show a tight period-luminosity relation among Cepheid variables in the Milky Way Galaxy.

- The most direct way to measure stellar distances is parallax. If you observe a nearby star in January and July when the Earth is on opposite sides of the Sun, the star's position will appear to shift with respect to distant stars. Based on the geometry, determining the star's distance is then just a matter of measuring its observed parallax angle.

- The Gaia observatory was launched by the European Space Agency in 2013 to precisely map the positions, parallax shifts,[¶] and proper motions of a billion Milky Way stars. With Gaia, the distances of stars out to 30,000 light-years can now be measured to an accuracy of 20% or better.

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§ Edwin Hubble's breakthrough discovery in 1925 that the Andromeda Galaxy was located far beyond the Milky Way was made possible by Henrietta Leavitt's SMC Cepheid relationship.

¶ Gaia can measure parallax angles down to the equivalent of the width of a human hair at a distance of 1000 kilometers!

- Although Gaia is not powerful enough to measure the parallax distances of other galaxies, Hubble has been very successful in measuring their Cepheid distances using this now-well-calibrated period-luminosity relation. Specifically, Hubble's sharp eye is absolutely vital in separating out the Cepheids in the crowded star fields of other galaxies and accurately measuring their brightness variations without contamination.

> The tandem of Gaia and Hubble observations now make Cepheid variables by far the best cosmic yardstick to determine the distances of galaxies within 100 million light-years. Furthermore, by establishing a large number of nearby galaxies with well-known distances, Cepheids have made it possible to calibrate the luminous explosions of supernovas as a much longer yardstick that can measure the universe over billions of light-years.

READINGS

Bartusiak, *The Day We Found the Universe.*
Christianson, *Edwin Hubble.*
Percy, *Understanding Variable Stars.*
Sobel, *The Glass Universe.*

QUESTIONS

1. How would the character of RS Pup's reflection nebula change if the star had the pulsation period (5.4 days) and luminosity (between 1200 and 2800 Suns) of Delta Cephei?

2. Would it be possible to use the Cepheid period-luminosity relation to determine the distance to a 10-billion-year-old star-rich globular cluster in the galactic halo?

Lecture 8

TRACING THE VEIL OF A PREHISTORIC SUPERNOVA

While Hubble can distinguish the light echoes of a sparkling nebula around a pulsating star, there are other optical nebulae in the Milky Way without such an obvious source of illumination. They typically exhibit a network of thin gas filaments woven together into larger-scale structures ranging in morphology from long arcs to nearly complete rings. These nebulae are the remnants of individual supernovas that occurred hundreds to thousands of years ago. Given their sky positions, some of these remnants can be traced back to the original explosions observed by our ancient ancestors on Earth.

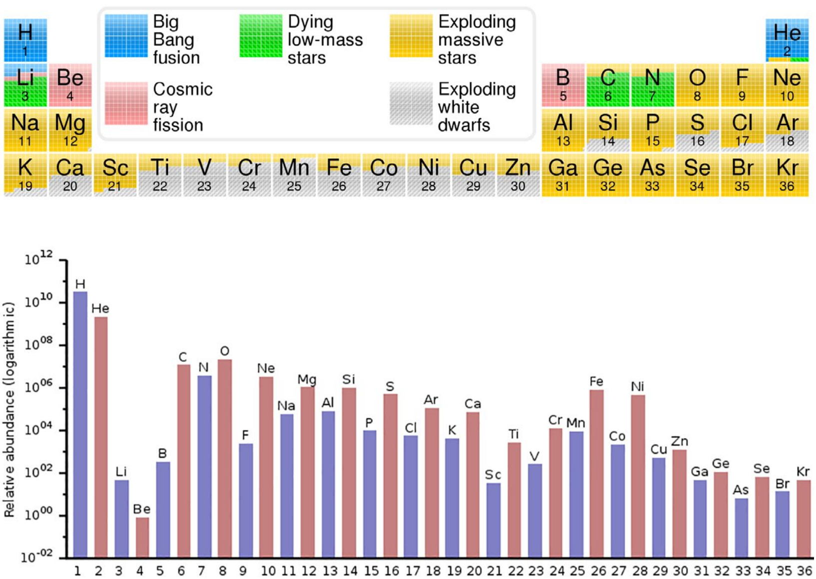
Elemental Composition of Stars

- As matter is recycled between stars and the interstellar medium through the processes of stellar evolution, both carry a signature of the elements forged in earlier generations of stars through their elemental composition.

- The relative abundance variations of the elements are due to their different nucleosynthetic origins over the history of the universe. Based on a number of theoretical and observational studies, we now have a much better understanding of these processes.

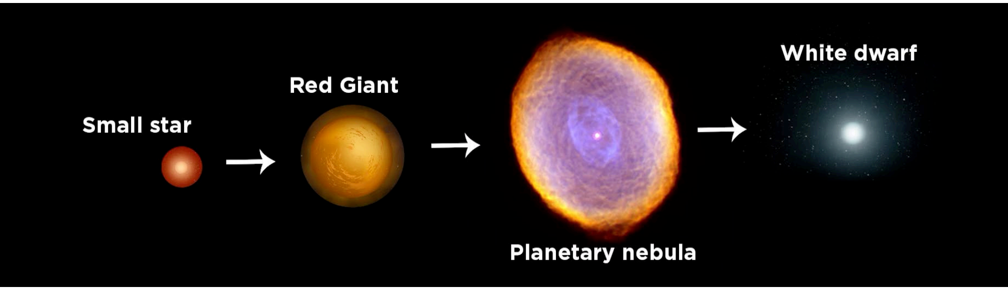
- In this color-coded top section of the periodic table of the elements [FIGURE 8.1], the origins of the lightest 36 elements are shown. It turns out that all of the hydrogen and almost all of the helium was forged in the first few minutes of the big bang, which began the universe 13.8 billion years ago. Essentially all of the other elements and some helium have been produced by stars since that time.

FIGURE 8.1



- Stars with initial masses less than 8 solar masses evolve off the main sequence as red giants. These low-mass stars lose a significant fraction of their mass to the interstellar medium as giants and planetary nebulae before becoming white dwarfs [FIGURE 8.2]. This mass loss is one important way through which they contribute nuclear-enriched material to the interstellar medium. It accounts for most of the carbon, nitrogen, and lithium in the Milky Way.

FIGURE 8.2



- The key route for some of the other elements is the occasional explosion of the white dwarf itself. In particular, these explosions mostly account for the galactic abundances of iron and adjacent elements on the periodic table.

- In the case of the first route, recall the formation of a planetary nebula like the Ring Nebula. Earlier episodes of fusion deep inside the progenitor red giant star left it with a mostly carbon core surrounded by hot shells of helium gas fusing into carbon and hydrogen fusing into helium. It is the energy pulses of the helium-fusion shell that blow off the outer layers of the star into a planetary nebula and eventually the interstellar medium. These layers include the nuclear-enriched material produced in the fusion shells, such as carbon.

- In the case of the exposed carbon core, it slowly cools as a new white dwarf star. The vast majority of such stars spend a rather boring eternity continuing to cool. However, an explosive alternative becomes possible if the white dwarf is closely orbiting another star in a binary star system.*

* About ½ of all stars in the Milky Way form as part of a binary or multiple-star system.

The Earth and all life on this planet owe their existence to ancient supernova explosions that predate the formation of the solar system 4.6 billion years ago.

Types of Supernova Explosions

- Let's consider how such a Type Ia supernova could occur. Note that a white dwarf is in hydrostatic equilibrium between gravity and electron pressure. A teaspoonful of a white dwarf's dense, carbon-rich gas would weigh a few tons on Earth. The electrons are packed so tightly in this dense gas that they exert a pressure that prevents gravity from squeezing the star below the size of Earth.

- However, if the mass of the white dwarf exceeds a value of 1.4 solar masses, its gravity becomes strong enough to overcome the electron pressure. This critical mass for a white dwarf is known as the Chandrasekhar limit.

- Imagine that we have a white dwarf just below this mass limit in a close binary system with a bloated red giant. The white dwarf's gravity will be strong enough to drain gas off the red giant's surface into an accretion disk that steadily adds mass to the dwarf star. When this mass gain enables the white dwarf to hit the Chandrasekhar limit, the dwarf will contract and heat up to the point where it ignites carbon fusion throughout the star. As a result, the entire white dwarf explodes.

- The mass gain essentially converts the white dwarf into a 1.4-solar-mass carbon-fusion bomb. The intense energy of the explosion rapidly forges iron and other elements out of the debris and expels this nuclear-enriched gas into the interstellar medium. Such Type Ia supernovas typically reach peak luminosities of 5 billion Suns, and such Type Ia explosions can be seen by Hubble out to distances more than 10 billion light-years.

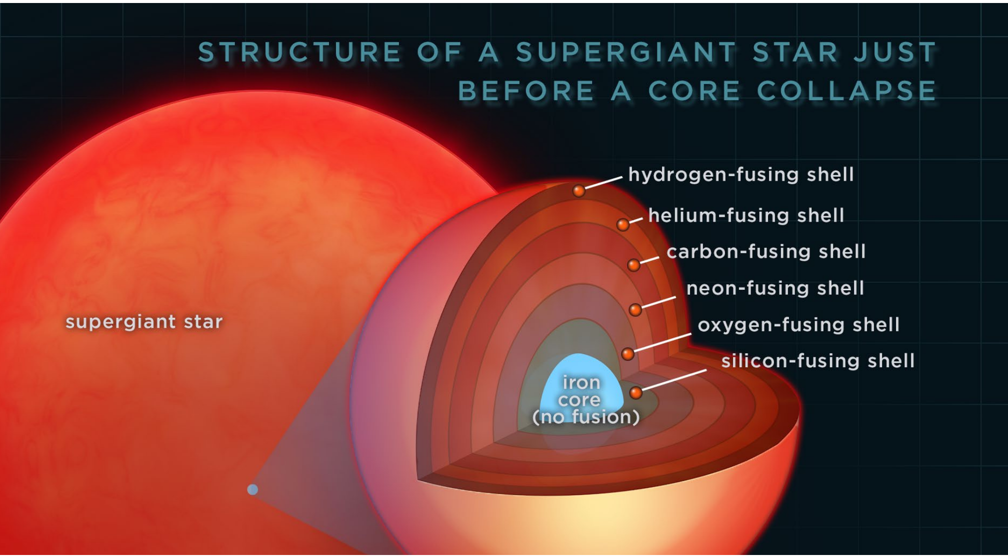
- All Type Ia supernovas have similar luminosity peaks and light curves. After quickly rising to peak luminosity, they slowly fade by a factor of 1000 over the course of a year. Their similarity in luminosity makes them the best cosmic yardsticks to the most distant galaxies.

- The other main supernova type occurs more frequently in spiral galaxies like the Milky Way. These Type II supernovas are less similar to each other than the Type Ia supernovas and are typically less luminous at peak brightness by a factor of about 5. In addition to the light curves, the 2 types of explosions exhibit other differences, such as the absence of hydrogen absorption lines in Type Ia spectra.

- The Type II supernovas are associated with stars that initially had masses greater than 8 Suns. These massive stars quickly evolve off the main sequence as supergiants. When supergiants explode as supernovas, they produce and expel elementally enriched gas into the surrounding interstellar medium. Among the 36 lightest elements, Type II supernovas contribute to the abundances of 32 of them. Indeed, they account for most of the oxygen, silicon, magnesium, aluminum, and potassium in the Milky Way.

- Some of this elemental production occurs during the star's life as a supergiant. Deep inside an old supergiant, its structure looks like an onion of concentric energy-producing fusion shells of different elements [FIGURE 8.3]. As the supergiant evolves, its core fuses heavier and heavier atoms, making the energy that holds off gravitational contraction.

FIGURE 8.3



The nearest supernova seen on Earth since 1604 was a Type II event in the Large Magellanic Cloud (LMC) on February 23, 1987. As the first supernova detected on the sky that year, it was given the label 1987A [FIGURE 8.4]. Despite the 160,000-light-year distance of the LMC, supernova 1987A was easily naked-eye bright at peak luminosity and remained so for months.

Hubble has observed supernova 1987A often since its 1990 launch to watch the remnant of the explosion grow.

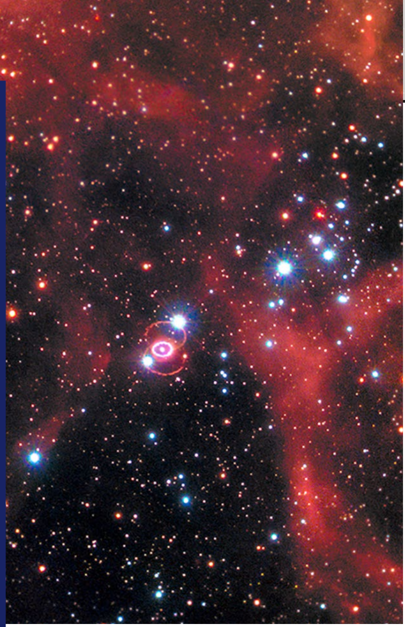


FIGURE 8.4

- Initially, the supergiant had a helium core. After all of the core helium fused to carbon, the core contracted, heated up, and began fusing carbon. As this cycle repeats with each new fusion product, the core gets steadily smaller, denser, and hotter. It also ignites the fusion of lighter elements in the surrounding gas shells.

- Eventually, the core becomes all iron, which is incapable of producing energy through fusion. As a result, its gravity collapses the iron core from Earth-size to city-size in less than a second. The infalling dense gas layers bounce off the core, and the outgoing shock wave reaches the stellar surface in hours. The energy of the explosion forges other elements in addition to those made earlier in the fusion shells. The explosion also expels all of this enriched gas far beyond the core into the interstellar medium.†

† Based on observations of supernovas in other galaxies, we should expect a Type II supernova in the Milky Way every 50 to 100 years. However, the last galactic supernova observed widely on Earth was a Type Ia event that occurred in 1604. There is evidence of more recent supernovas in the Milky Way, but they occurred in distant disk regions heavily obscured by intervening dust.

The Veil Nebula

- Among the 300 supernova remnants currently known in the galaxy, the Veil Nebula [FIGURE 8.5] is one of the largest on the sky, with a diameter equivalent to 6 Moons. Although it is too faint to see with the naked eye, the Veil Nebula is located on the sky near the Northern Cross in the Cygnus star constellation. Due to the Veil Nebula's large size and shape on the sky, it is sometimes referred to as the Cygnus Loop.

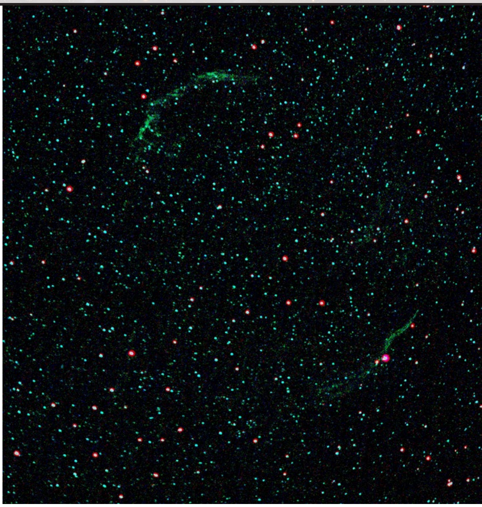


FIGURE 8.5

- There is no written record in human history of the supernova corresponding to the Veil remnant. Thus, it is not possible to identify the supernova as a Type Ia or a Type II based on the explosion itself. However, given the remnant's expansion rate and its distance of 2400 light-years, it appears to be about 10,000 years old. The supernova exploded in a region just above the galactic disk with a relatively low density of interstellar gas.

- As viewed at optical wavelengths today, the 130-light-year-wide remnant is not a complete ring or shell. Its large central cavity reflects both the low interstellar density and the possible strong wind of the supernova progenitor. The remnant is exhibiting optical emission at only those places where the supernova ejecta are colliding with the interstellar gas and exciting it to glow.

- Due to the Veil Nebula's large sky size of 3°, it has not been imaged in its entirety by Hubble. Instead, the space telescope has focused on the nebula's small-scale structure in several well-separated regions.

- The first of these regions is at the very edge of the remnant just beyond the bright eastern arc on the upper left [FIGURE 8.6].

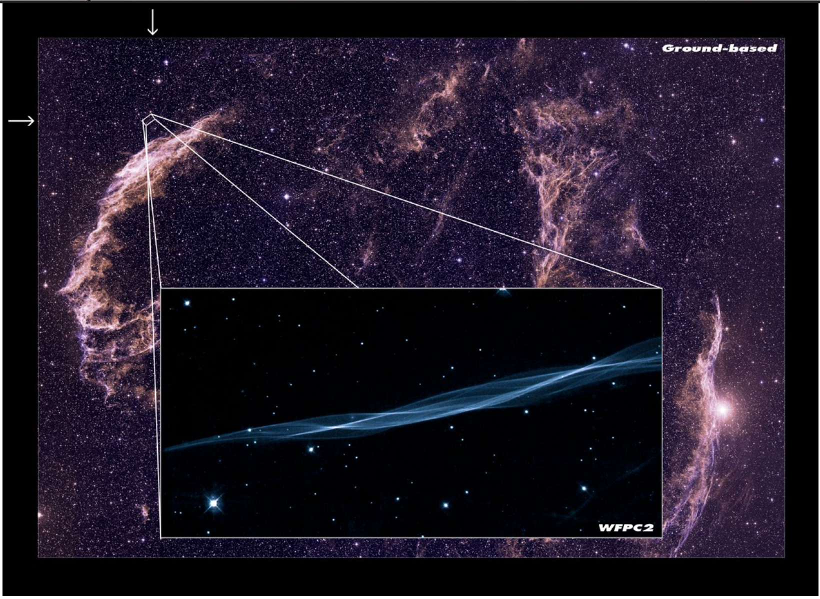


FIGURE 8.6

- This Hubble close-up reveals a beautiful braid of hydrogen emission from a 2-light-year-long set of twisted filaments [FIGURE 8.7]. The thinnest individual filaments are at the 100 AU limit of Hubble's resolution. This apparent braid of filaments is interpreted as a gently rolling sheet of gas seen almost exactly edge-on. The observed rippling effect is due to slight variations in the density of the gas impacted by the supernova shock wave.

FIGURE 8.7

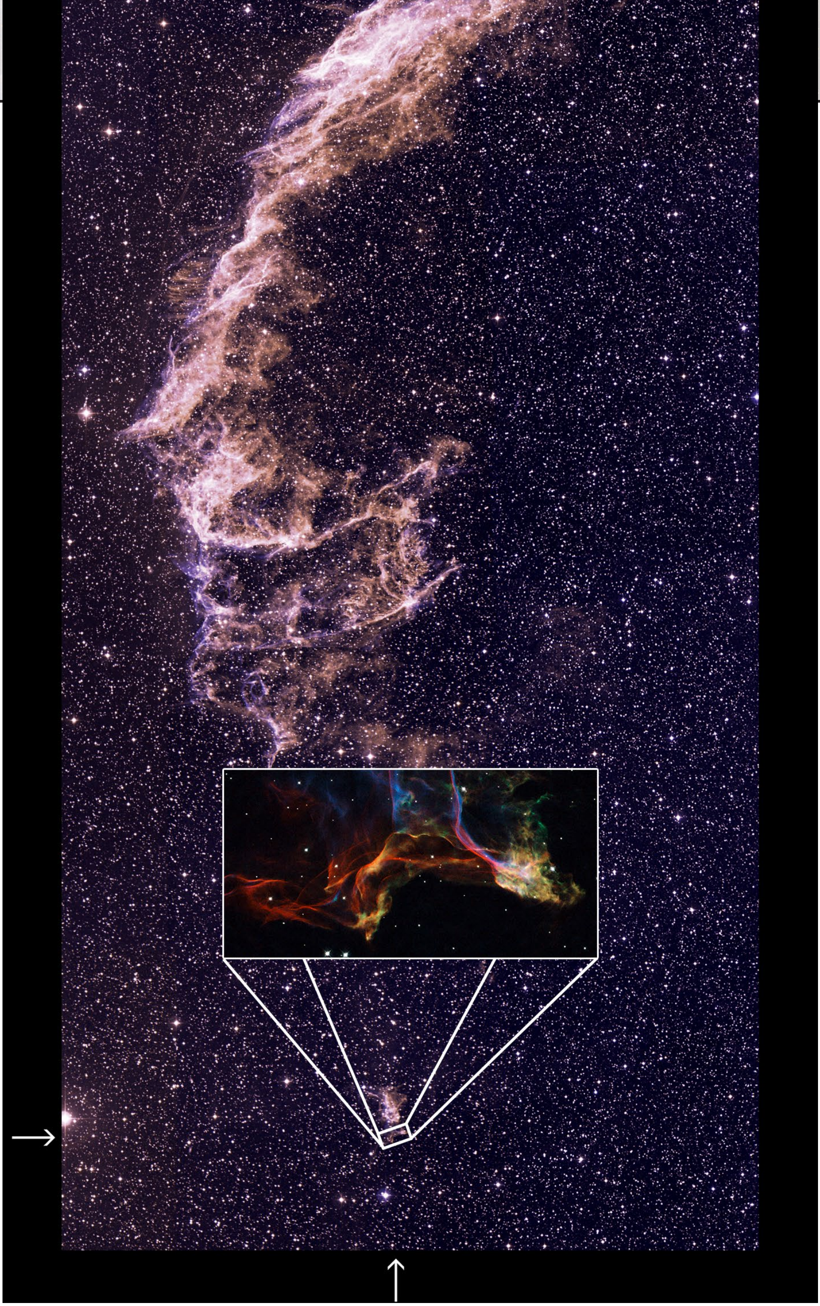


FIGURE 8.8

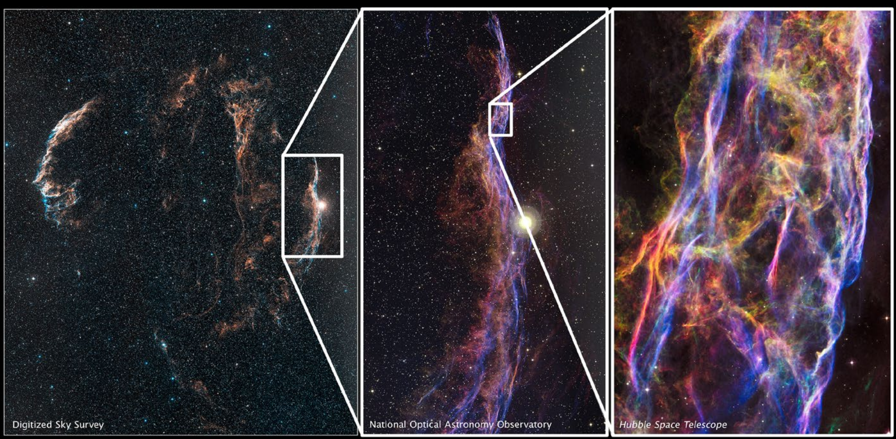
FIGURE 8.9

- The second region of focus is a piece of a nebular knot below the bright eastern arc [FIGURE 8.8]. This Hubble close-up [FIGURE 8.9] is also 2 light-years across, and it shows more turbulent gas than the first region.

- The blue, green, and red colors correspond to emission from oxygen, sulfur, and hydrogen, respectively. Note that sharp filaments and areas of diffuse emission are the 2 basic gas structures observed in the image. The filaments and diffuse patches are interpreted as tracing edge-on and face-on views of the shocked gas. Overall, this nebular knot appears to be the complex result of the supernova debris colliding with a small interstellar cloud.

The brightest supernova ever recorded on Earth occurred in the year 1006. With a peak brightness 250 times greater than the star Sirius, this supernova could be seen during daytime for weeks and remained visible to the naked eye for 2.5 years.

FIGURE 8.10



- Hubble has revealed even greater complexity in a region of the bright arc on the west side of the Veil Nebula. As we zoom from a large-scale view of the entire nebula on the left to the small-scale Hubble view on the right [FIGURE 8.10], note the background star counts on either side of the bright arc in the middle image. The fewer counts on the right of the arc are consistent with the supernova shock slamming into a large, denser, dustier cloud in this remnant region. The brightness of the arc and its turbulent structure indicate that the interaction between the shock wave and this cloud has been going on for quite some time.

FIGURE 8.11

- This Hubble close-up [FIGURE 8.11] is a summed mosaic of 90 images with a total exposure time of more than 10 hours. It spans a nebular region that is about 5 light-years across. The blues, greens, and reds in this colorful image reflect emission from the oxygen ions, sulfur ions, and excited hydrogen atoms in the nebula.

- The orientation of the nebula in this image is such that the supernova blast wave is traveling from the lower right to the upper left. Furthermore, we are seeing complex 3-dimensional structure in 2 dimensions. Specifically, the fainter emission on the upper left of the image is most likely due to gas beyond the main filament.

- In the case of the main filament, note that the blue oxygen emission typically looks more distinct and linear in structure. In comparison, the green and red emission from sulfur and hydrogen looks more diffuse and often mixed. The physical interpretation of this color scheme is that the oxygen emission arises in hotter gas nearest the supernova shock wave while that of sulfur and hydrogen is seen in the cooler gas behind the shock front.

- Scientists have determined that the supernova blast wave is still moving at a velocity of 400 km/s some 10,000 years after the explosion. But what type of supernova produced this expanding remnant?

- A key to answering this question comes from x-ray observations of the remnant. Let's compare the ground-based optical view of the entire Veil Nebula [FIGURE 8.12] with that taken by the ROSAT x-ray space telescope [FIGURE 8.13]. The x-ray image shows bright emission corresponding to many of the shocked optical edges of the remnant. It also shows diffuse x-ray emission from the hot gas inside the remnant.

- Furthermore, the x-ray spectra show higher abundances of heavy elements inside the remnant than at its edge. This inside spectrum reflects the abundances of the supernova ejecta alone, while that at the edge reflects an interstellar mixture. The resulting elemental abundance pattern inside the Veil Nebula clearly indicates that it is a remnant of a Type II supernova explosion. In this way, a supernova remnant can provide an autopsy of its progenitor's death.

FIGURE 8.12

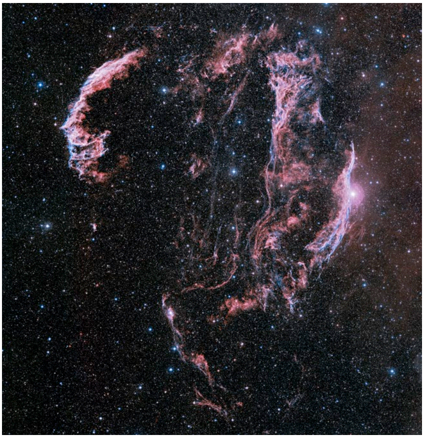
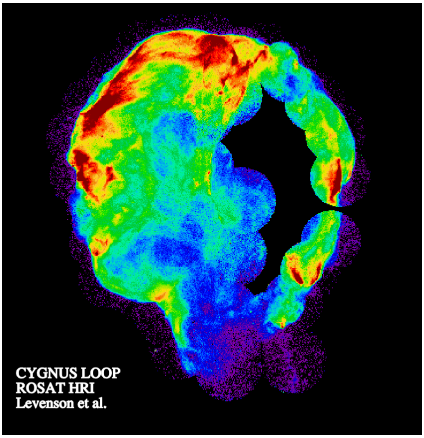


FIGURE 8.13



The Big Picture

- During the 230 million years that the galactic disk takes to complete a single rotation, about 3 million supernovas occur, with about 70% of them being Type II. Since their massive progenitors are short-lived, these Type II supernovas occur close to the spiral arms, while the Type Ia supernovas are spread throughout the disk.

- On timescales of many thousands to millions of years, each violent supernova explosion shapes its immediate interstellar surroundings and turbulently mixes in heavier elements. On timescales of about 50 million years, the diffuse, enriched debris in each region is compressed by a spiral density wave into dense, star-forming clouds—and the cycle repeats. The net result is a galaxy producing new stars of slowly increasing metallicity amid an elementally well-mixed interstellar medium.

READINGS

Branch and Wheeler, *Supernova Explosions.*
Frebel, *Searching for the Oldest Stars.*
Hartquist, Dyson, and Ruffle, *Blowing Bubbles in the Cosmos.*
Kirshner, "The Supernova of a Lifetime."

QUESTIONS

1. From the perspective of the galactic center, when did or when will the supernova explosion responsible for the Veil Nebula occur?

2. Which type of supernova is most likely to occur in the star-forming regions of the Milky Way?

Lecture 9

THE STELLAR VORTEX AT THE GALACTIC CENTER

The galactic center is located on the sky where the glow of the Milky Way is widest in the constellation Sagittarius. At its distance of 27,000 light-years, the galactic center is not observable at optical wavelengths due to a thick shroud of intervening stardust. However, as viewed in the near-infrared with Hubble, the heart of the Milky Way is found to be ablaze with stars. The stellar density in the cluster is a million times greater than that in the solar neighborhood. Yet an even denser core of darkness resides within this brilliant star cluster. As measured with large ground-based telescopes, the rapid motion of the centermost stars indicate that they are orbiting a central black hole with a mass of 4 million solar masses.

The Galactic Center Star Cluster

- As viewed on the large scale, our galaxy consists of several components that differ in their size, stellar composition, and interstellar characteristics but all share the same dynamic center.

- Like other spiral galaxies, the disk of the Milky Way is distinguished by the active star formation associated with the dense interstellar clouds of gas and dust in its spiral arms. Our tour of the Milky Way to date has primarily focused on the formation and evolution of stars in the galactic disk within 15,000 light-years of the Sun.

- As viewed edge-on, the disk itself can be thought of as having 2 components:

  - The thin disk is about 2000 light-years thick. It contains mostly young stars known as Population I stars and most of the interstellar gas and dust in the entire disk. These Population I stars formed from the elementally enriched gas ejected into the interstellar medium by earlier generations of stars. Thus, they have higher abundances of heavy elements than their ancient stellar ancestors.*

  - Surrounding the thin disk is a thick disk of mostly older Population I stars. It is about 6000 light-years thick, with a star density that is just 10% of that in the thin disk.

- Surrounding the thick disk is a large stellar halo of mostly Population II stars, which are very old stars with very low abundances of heavy elements. This region extends tens of thousands of light-years above and below the disk. It has very little interstellar material and essentially no ongoing star formation. The total stellar mass in the galactic halo is only a few percent of that in the disk. About 1% of this stellar halo mass is tied up in 200 well-separated, rich clusters of stars known as globular clusters.

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* The Sun is a Population I star.

- The general trend of increasing stellar metallicity from the halo to the thin disk is likely telling us something about the formation and evolution of the Milky Way. Indeed, based on studies of distant galaxies, we can imagine the appearance of the Milky Way early in its history. The galactic disk of interstellar gas was much thicker, with initial pockets of star formation reaching well into the halo.

- As this gas gravitationally settled into a thinner disk, star formation accelerated and became more concentrated in the disk. The Milky Way thus built up about 90% of its stars between 7 and 11 billion years ago. The recent slower star formation since that time has focused in the thin disk building up its concentration of Population I stars.

- In terms of both its appearance and stellar population, the central bulge of the Milky Way is rather distinct from the disk. The bulge is about 15,000 light-years across, with a stellar mass that is about 20% of that in the disk.

- The largest structure in the bulge is a thick stellar bar. It is oriented at an angle of about 45° from our line of sight inside the disk. This orientation gives the bulge of the Milky Way a rather boxy or peanut-like appearance. It is believed that the central bar formed through the gravitational perturbation of the bulge stars into elliptical orbits around the galactic center.

FIGURE 9.1

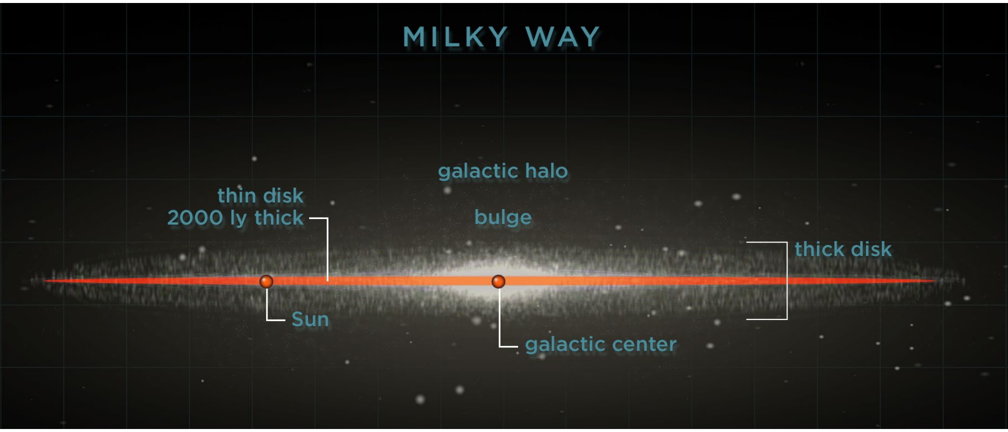


FIGURE 9.2

- Viewed optically [FIGURE 9.2], the glow of the galactic bulge on the sky is wider and brighter than that of the adjacent disk. The dust seen toward the bulge is mostly in the intervening thin disk. This thick dust screen blocks our optical view of the galactic center and its surrounding region deep inside the bulge. Fortunately, there are some small dust-poor windows into the bulge that lie within a few degrees of the galactic center.

- This optical close-up on the bulge [FIGURE 9.3] illustrates the position of the galactic center relative to the well-known teapot of bright stars making up the Sagittarius constellation.

FIGURE 9.3

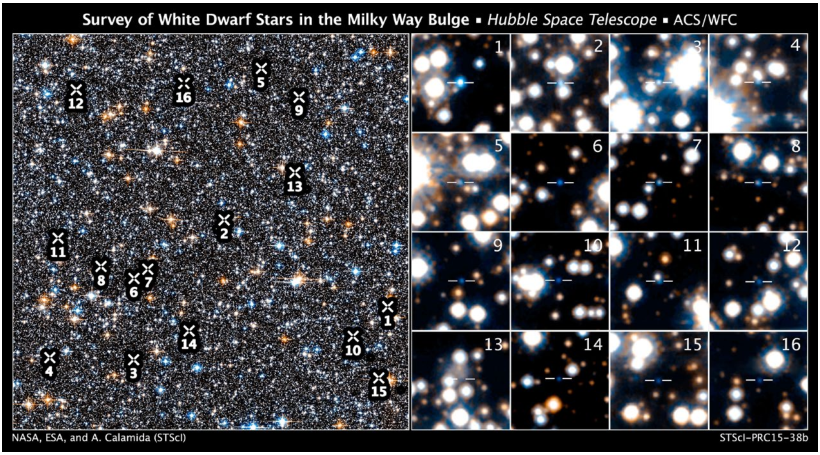
- Hubble has taken several deep exposures in some of the dust-poor bulge windows. One of them is known as the Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS) field, which covers a sky area equal to about 1% that of the Moon.

- The Hubble image resolves out an amazing 200,000 stars in this tiny field [FIGURE 9.4]. The vast majority of these stars are located in the bulge. By comparing their colors and brightnesses, it is possible to construct a Hertzsprung-Russell diagram for this region of the bulge and determine the ages of its stellar population.

FIGURE 9.4

- The SWEEPS image also reveals a number of white dwarfs [FIGURE 9.5]. Only Hubble has the ability to resolve out such faint stars in crowded star fields. These white dwarfs are the remnants of stars born more than 12 billion years ago. Indeed, it turns out that most of the SWEEPS stars belong to an ancient stellar population. These results are consistent with the idea that the central bulge formed early in the history of the Milky Way.

FIGURE 9.5



- Nevertheless, some of the bulge stars are younger, with higher abundances of heavy elements. Based on comparisons between Hubble images taken years apart, these younger stars also appear to be moving faster than the older ones. It is possible that these stars may have originated in small satellite galaxies that were gravitationally cannibalized by the Milky Way after the primary star formation epoch in the bulge.

- Unfortunately, the optical characteristics of the stellar population in the centermost region of the bulge are impossible to measure due to the thickness of the intervening dust toward the galactic center.

- Nevertheless, this Hubble image [FIGURE 9.6] maps out a 50-light-year-wide square at the 27,000-light-year distance of the galactic center. Its depth takes full advantage of the sensitive near-infrared capability of Hubble's Wide Field Camera 3. The image is actually a mosaic of 9 separate star fields observed by this camera. Overall, it represents a sum of more than 100 exposures in 3 near-infrared colors spanning a total observing time of 21.6 hours. The color scheme of the final image is designed such that the shortest-wavelength near-infrared color is shown as blue and the longest is shown as red.

- Note the colors of the stars and the dark patches across the image. The bluish stars are typically foreground stars least attenuated by dust. The dark patches are the thickest dust regions that are impenetrable to Hubble's near-infrared eye. The reddish stars are typically behind much of the dust or embedded in it.

FIGURE 9.6

- As we zoom into the central 16 light-years, note the star concentration at the center of the image [FIGURE 9.7]. This concentration is the core of the Milky Way's nuclear star cluster. Almost all of the stars outside the dark patches in this image are part of the cluster. The image yields a count of about 500,000 stars within the cluster radius of 15 light-years. Based on the colors and brightnesses of these stars, the cluster must include another 10 million stars too faint to have been seen by Hubble. The resulting total mass of 25 million Suns for the nuclear star cluster makes it the most massive cluster in the Milky Way.

FIGURE 9.7

- Like the surrounding galactic bulge, most of this cluster's stars are very old. However, the cluster also contains some young stars, particularly near its core.

- As we zoom into the inner light-year of the cluster core at the galactic center, we reach the resolution limits of even Hubble's sharp eye. Indeed, there are so many stars in this region that their images blend together. The stellar density here is so high that the typical star separation is only about a light-week—instead of the light-years that separate stars in the solar neighborhood.

At the darkest observing sites on Earth, the star Sirius is brightest among the 3000 or so stars visible to the naked eye. At the galactic center, Earth's night sky would have a million stars brighter than Sirius. Collectively, this starlight would be 200 times brighter than the Moon!

Supermassive Black Holes

- The core collapse of a massive star produces a Type II supernova explosion. If the star's initial mass was between 8 and 25 solar masses, its core will most likely collapse into a neutron star. If its mass was greater than 25 solar masses, the core collapse will typically result in the formation of a black hole.

- A neutron star is a city-size object composed of about 1.5 solar masses of neutrons. It's much denser than a white dwarf. A teaspoonful of neutron star material would weigh a billion tons on Earth. The extreme neutron pressure at this density prevents gravity from squeezing the neutron star to an even smaller size. This gravitational field is so intense that the velocity necessary to escape from a neutron star surface is ⅓ of the speed of light.

- An even more extreme situation occurs when the cores of the most massive stars collapse. In this case, there is nothing known that can hold off the relentless force of gravity.

- As a result, the entire core is crushed into a point called a singularity. The Schwarzschild radius is defined as the distance from the singularity where the escape velocity from this gravitational prison is equal to the speed of light. This radius defines the size of the event horizon surrounding the singularity. Essentially, the event horizon represents the surface of a black hole. Inside this horizon, nothing—not even light—can escape the gravitational field of the singularity. That's why it's called a black hole.†

† A typical 10-solar-mass black hole has a Schwarzschild radius of 30 kilometers. It is estimated that the Milky Way contains about 100 million of these stellar black holes produced by the explosions of individual Type II supernovas.

- A key question is how, if at all, such relatively low-mass stellar black holes figure into the production of the 4-million-solar-mass black hole at the galactic center. Even the collapse of the most massive stars known can't produce a black hole with a mass more than about 100 solar masses.

- The leading ideas in addressing this question create a massive black hole seed at the galactic center when the Milky Way was very young. One version is that a massive stellar black hole could collide and merge with other stellar black holes in a dense star cluster. The resulting middleweight black hole with the mass of 10,000 Suns could then continue to grow by swallowing up stars and gas clouds that come its way.

- Another possibility in seeding the formation of the galactic center black hole is to completely bypass the middle step of forming stellar black holes first. This idea involves the direct collapse of a primordial, dense, massive gas cloud into a middleweight black hole. This object then grows into a supermassive black hole over time by eating the stars and gas clouds that fall into its gravitational well.

- There is strong evidence that the 4-million-solar-mass black hole at the galactic center continues to eat, albeit modestly. Such a black hole has an event horizon that measures about 0.2 AU in diameter.

- Given the high density of stars at the galactic center, the supermassive black hole occasionally gets a big meal. A close-passing star can be tidally disrupted by the black hole and produce a huge outburst of light. However, there is no evidence of such a feast recently. The current best estimate is that the supermassive black hole devours a star every 100,000 years.

- Based on Hubble observations of high-velocity stars and gas in the nuclei of a variety of galaxies, it is now clear that essentially all spirals and large ellipticals have a supermassive central black hole.

- In addition, there is a strong correlation between the mass of the black hole and the mass of the stars and gas in the central bulges of these galaxies. This correlation shows that supermassive black holes coevolve with their host galaxies in the sense that the more massive black holes had more stars and gas clouds to eat.

- In other words, the central black hole's mass is not primordial; it grows as the galaxy evolves. As a result, spiral galaxies with small central bulges, like the Milky Way, have rather wimpy supermassive black holes with only a few million solar masses. In contrast, giant elliptical galaxies have enormous central black holes with masses of a few billion Suns.

READINGS

Bartusiak, *Black Hole*.
Bland-Hawthorn and Gerhard, "The Galaxy in Context."
Fletcher, *Einstein's Shadow*.
Greene, "Goldilocks Black Holes."

QUESTIONS

1 Given the mass correlation between the central black holes and stellar bulges of galaxies, how would our night-sky view of the Milky Way be different if the galaxy's core had a much larger black hole with the mass of a few billion Suns?

2 If the Earth were positioned within a few light-years of the galactic center, would the Milky Way be apparent to the naked eye in the night sky?

Lecture 10

THE GALACTIC HALO'S LARGEST STAR CLUSTER

Beyond the galactic center, the oldest, densest star clusters in the Milky Way are typically found outside the star-rich galactic disk. These ancient globular clusters stand out like compact islands of stars in the sparse stellar sea of the galactic halo. Unlike the galactic center star cluster, there are essentially no intervening dust clouds to obscure Hubble's sharp view of the stars making up these densely packed clusters.

Globular Clusters

- A total of 200 globular clusters have been identified to date in the Milky Way Galaxy. Almost all of them are located in the galactic halo at distances ranging from 7000 to more than 100,000 light-years. The globulars have a roughly symmetrical halo distribution relative to the galactic center, which they orbit with typical periods of 100 million years or more.

- In addition to the globulars, the Milky Way has another broad group of star clusters collectively known as open clusters. The disk of the Milky Way has thousands of open clusters, each consisting of dozens to thousands of stars.

- Let's compare some of the characteristics of the 2 basic types of star clusters found in the Milky Way. The globular clusters typically have 100 to 1000 times more stars than the open clusters. Their stars are densely packed into spherical arrangements, while the open clusters have irregular shapes with a range of stellar densities. The globulars consist of ancient stars that formed when the Milky Way was very young; most of the open clusters consist of young stars that recently formed in the spiral arms of the Milky Way. Consequently, the open clusters are typically found in the galactic disk, while the globulars reside in the galactic halo.

- Despite these differences, globulars have some similarities to open clusters. The stars in both types of clusters are held together as a group by their mutual gravity. In addition, it's a good approximation to assume that the stars in any cluster all formed together at about the same time. Thus, the age of any cluster can be determined by comparing the colors and brightnesses of its constituent stars in a Hertzsprung-Russell (HR) diagram. Hubble's ability to resolve out the tightly packed stars in globulars makes it key to studying these clusters.

- Among the globular clusters imaged by Hubble, NGC 6397 [FIGURE 10.1] is one of the closest. It is located below the disk of the Milky Way in the southern constellation Ara at a distance of 7800 light-years. It contains about 200,000 stars and has a diameter of about 70 light-years.

FIGURE 10.1

- By accurately measuring the turnoff point on the cluster's main sequence, the cluster's age can be determined from its HR diagram. NGC 6397's Hubble HR diagram indicates an age of 13 billion years, making it one of the oldest globular clusters in the Milky Way. In comparison, the universe began with a big bang 13.8 billion years ago. Thus, the 200,000 stars in this globular must have formed in a quick burst less than 1 billion years after the big bang. The HR diagrams of the other globular clusters in the Milky Way indicate that they developed within a few billion years after NGC 6397.

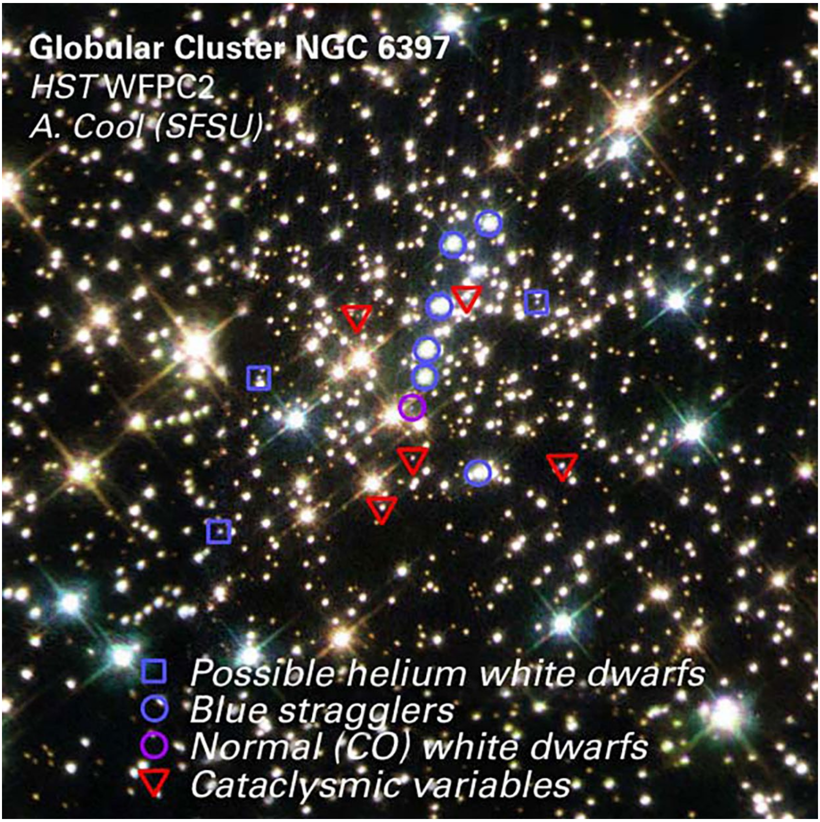
- The Milky Way itself originated through the gravitational accretion of large, massive gas clouds about 13 billion years ago. Ancient globular clusters such as NGC 6397 likely formed as part of this process, through the starbursts arising from collisions between these clouds.

- In addition, some of the globulars may have been accreted then as part of small gas-rich galaxies. As the massive amount of gas in the young Milky Way gravitationally settled into a rotating disk, both the native and the accreted globular star clusters remained behind in halo orbits. Thus, the globular clusters are ancient fossils dating back to the formation of the Milky Way.

- In addition to their extreme age, globular clusters are also noteworthy for the high density of stars in their core regions.

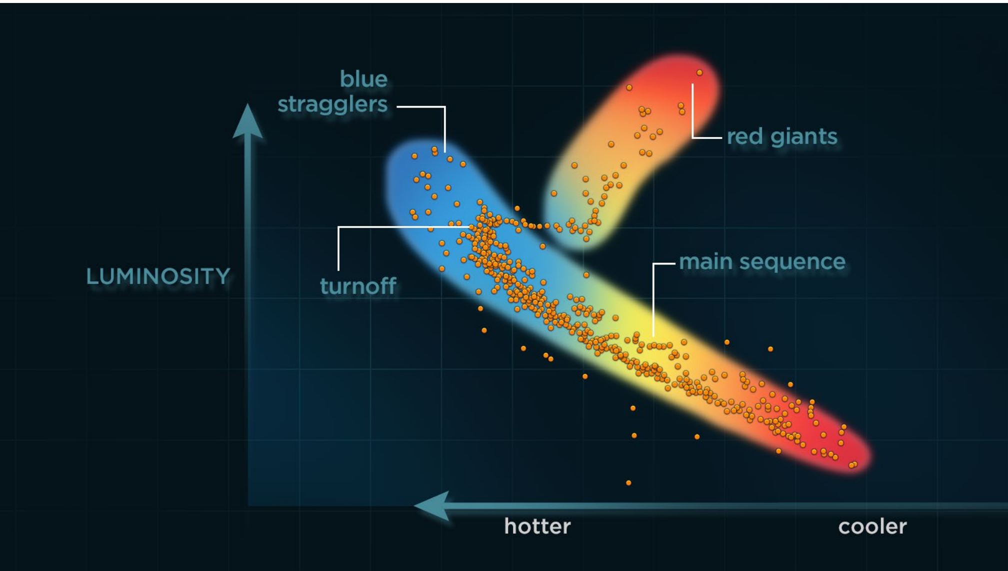
- This high density is certainly apparent when we zoom into the central 2 light-years of NGC 6397 with Hubble [FIGURE 10.2]. The average separation between these stars is only a few light-weeks. The stars are so crowded that collisions or near misses happen about every million years. This rate works out to thousands of close stellar interactions over the lifetime of the cluster.

FIGURE 10.2



- Such interactions can lead to a type of star known as a blue straggler. Circled in blue, 6 of these relatively bright stars stand out in the Hubble image of the cluster core. Blue stragglers also stand out in the HR diagram of a globular cluster [FIGURE 10.3]. In terms of their colors and luminosities, these stars form a sparse group on the diagram that is located above the well-populated main-sequence turnoff point of the cluster. In other words, these blue stars appear to be younger than the rest of the stars in the globular. How is it possible for such stars to find a fountain of youth?
    - The most direct route is a collision between 2 stars. The stars then merge, mix their core hydrogen fuel, and shine as a single star that is more massive and hotter than either of its parents.
    - A blue straggler can also form from a close binary star system. As the higher-mass star evolves into a red giant, the lower-mass star gravitationally drains the expanding hydrogen envelope of its companion. With the added mass, the accreting star becomes hotter, bluer, and more luminous.
- In both cases, the resulting blue straggler ends up with about twice the mass of a typical globular cluster star.

FIGURE 10.3



- As a globular cluster ages, its higher-mass stars tend to sink inward toward its core. This migration results from gravitational interactions with the closely packed surrounding stars. As a consequence of these interactions, the general tendency is for the higher-mass stars to lose orbital energy and for the lower-mass stars to gain it.

- Thus, since their masses are higher than average, the blue stragglers in a globular cluster tend to settle toward its core over time. Those stragglers closest to the higher-density core are the first to migrate inward. At the same time, the lower-mass stars puff out the cluster's stellar outskirts.

- Consequently, the stars in the core of a globular cluster become more tightly bound over time, while those in its outer regions become more loosely bound. The rate at which this gravitational star sorting occurs varies from globular to globular. About 20% of the globular clusters in the Milky Way have reached the point where more than ½ of their mass is in the core. Such core-collapse globulars are characterized by a sharp peak in their core luminosity.

- The most famous example of a core-collapse globular cluster is Messier 15 (M15) [FIGURE 10.4], which is located below the Milky Way in the Pegasus star constellation at a distance of about 34,000 light-years. Overall, the cluster has more than 100,000 stars spanning a diameter of 175 light-years. The cluster's HR diagram indicates that M15 has an age of about 12 billion years.

FIGURE 10.4

- The core collapse of this globular has concentrated ½ of its mass in the innermost 10 light-years. The core region of M15 is one of the densest among the globular clusters in the Milky Way. Indeed, the stars are so densely packed at the center of M15 that not even Hubble can resolve them.

- Given this extreme density, some have argued that M15 may have a central black hole. The confirmation of such a black hole at the core of M15 could help in understanding the origin of the supermassive black hole at the galactic center.

- Despite their stellar density differences, both M15 and NGC 6397 have stellar populations that are quite similar. The stars in both clusters all formed quickly together within a few billion years after the big bang. They are all Population II stars with metal abundances that are less than 1% of those in the Sun. These characteristics are consistent with M15, NGC 6397, and many other globulars, having been part of the Milky Way since its formation. However, it now appears that perhaps 40% of the globulars were accreted by the galaxy at later times.

Omega Centauri

- There is strong evidence that Omega Centauri‡ is one of these accreted clusters. It certainly stands out as the richest and most massive globular by far in the Milky Way. It can easily be seen with the naked eye, despite its distance of 16,000 light-years. Nevertheless, it takes the sharp eye of Hubble to resolve out the tightly packed stars of Omega Centauri and study its true nature.

> Omega Centauri is the brightest globular cluster in the sky. Located just above the Milky Way in the southern sky about 17° away from Alpha Centauri, it is so bright and compact that it can be seen with the naked eye.

‡ Omega Centauri has a starlike name because pre-telescope astronomers long ago misidentified it as a single star.

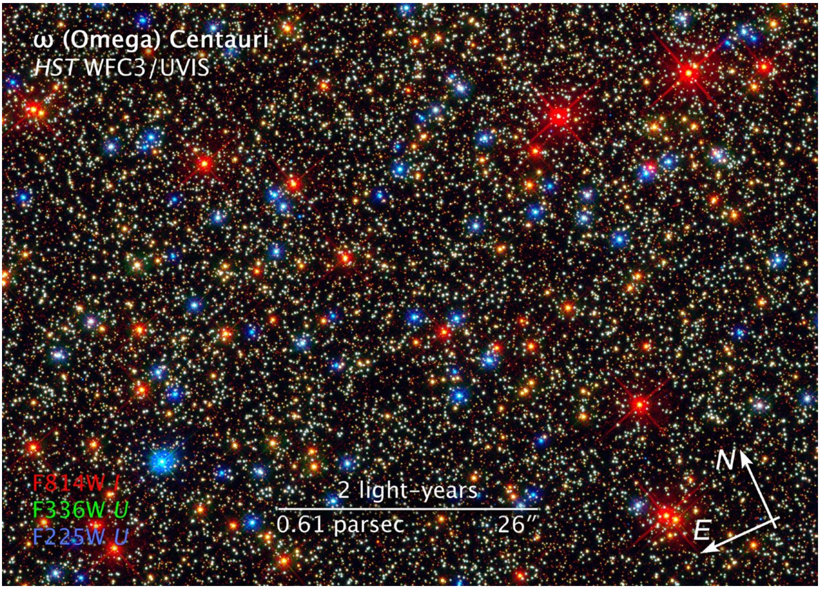
- Hubble has observed this globular multiple times with different instruments. This optical view of its centermost 50 light-years [FIGURE 10.5] was taken with its Advanced Camera for Surveys. It is a mosaic of 9 overlapping star fields observed in both blue and red light. The composite image involves the sum of 54 individual exposures spanning 5 hours of observing time. The total number of stars in this image is 2 million, and it covers just the core of Omega Centauri. Overall, the cluster has a total of 10 million stars spanning a diameter more than 200 light-years across.

- Omega Centauri has not undergone a core collapse similar to that of M15 and NGC 6397. Yet the central stellar density of this globular is comparable to that of M15 but over a much larger volume.

FIGURE 10.5

- The innermost core of Omega Centauri has also been imaged with the Wide Field Camera 3 onboard Hubble. This 6-light-year-wide view [FIGURE 10.6] is a sum of multiple exposures taken at ultraviolet and near-infrared wavelengths that span a total of 2.7 hours of observing time. The shortest- and longest-wavelength ultraviolet colors are shown as blue and green, respectively. The near-infrared color is shown as red. This color scheme is designed to accentuate the hottest stars as blue and the coolest stars as red.

FIGURE 10.6



The stars in the core of Omega Centauri are 50 times closer to each other than the Sun is to its nearest stellar neighbor.

- Detailed studies of the Hubble HR diagram for Omega Centauri show evidence of multiple main-sequence turnoffs. In other words, it appears that all of the stars in this globular didn't form at about the same time. Specifically, it consists of multiple generations of stars born between 10 and 12 billion years ago. Furthermore, the spectra of these Population II stars show a large range in their heavy-element abundances. Some have abundances that are only 2% that of the Sun, while others have 10 times that much.

- Based on these stellar characteristics and the cluster's huge mass of 5 million Suns, it is now clear that Omega Centauri is not a globular native to the Milky Way. It is most likely the core of a dwarf spheroidal galaxy gravitationally captured by the galaxy about 10 billion years ago.

- Such dwarf galaxies are commonly found today and typically have tens of millions of stars spanning diameters of about 1000 light-years. Some of them are known satellites of the Milky Way orbiting at distances of more than 100,000 light-years. But if Omega Centauri was originally a dwarf galaxy, where's the rest of it now?

- As part of its effort to precisely map the positions, parallaxes, and motions of a billion stars out to distances of about 30,000 light-years, the Gaia space observatory has measured the motions of 75 globular clusters and 12 dwarf galaxies. Although these objects are typically located beyond the optimal range of Gaia's measurement accuracy, the results are still good enough to provide unprecedented information on the direction and magnitude of their motions.

- In this all-sky map [FIGURE 10.7], the arcs from each object denote its future projected motion. The globular clusters are identified by the blue arcs, whose lengths correspond to their projected sky movement over the next 10 million years. The red arcs represent the sky movement of the dwarf galaxies over the next 100 million years. The large X marks the current location of Omega Centauri on the map. Its projected orbital motion shows that it will be passing through the galactic disk more than 10 million years from now.

→ GAIA'S GLOBULAR CLUSTERS AND DWARF GALAXIES
(next 10 million years) (next 100 million years)

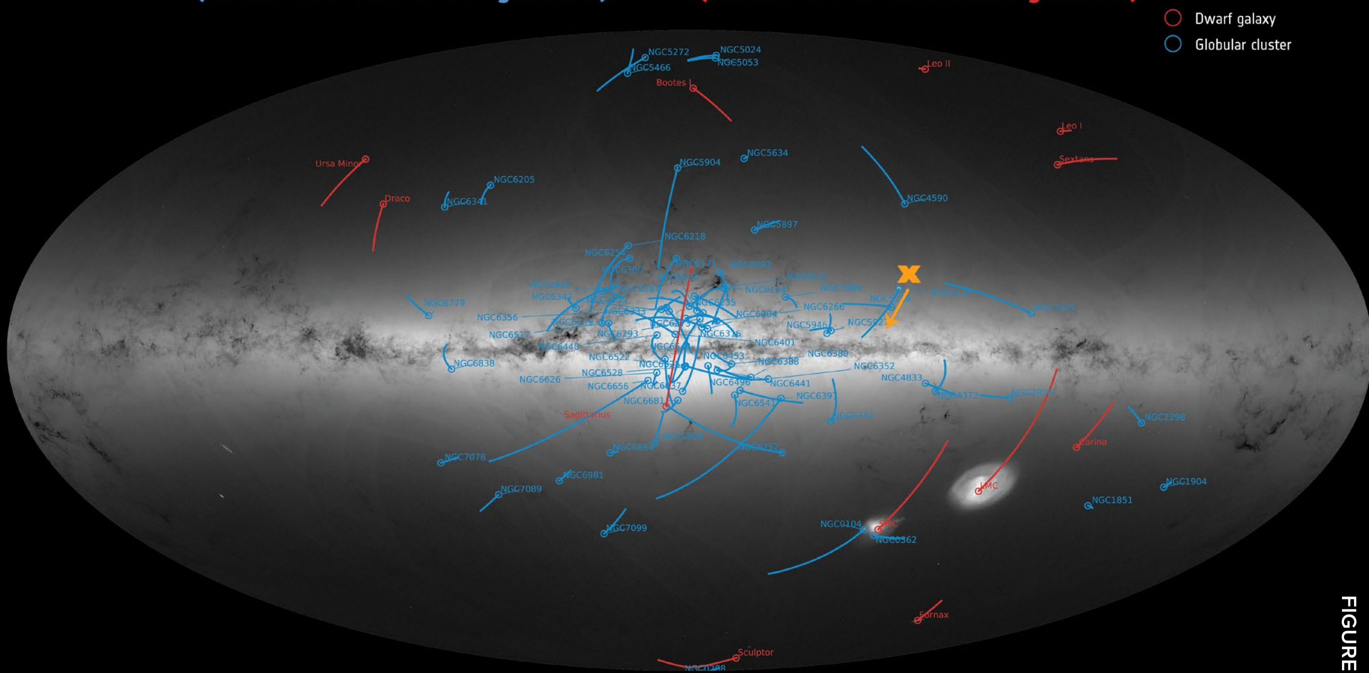


FIGURE 10.7

www.esa.int

Credit: ESA/Gaia/DPAC

European Space Agency

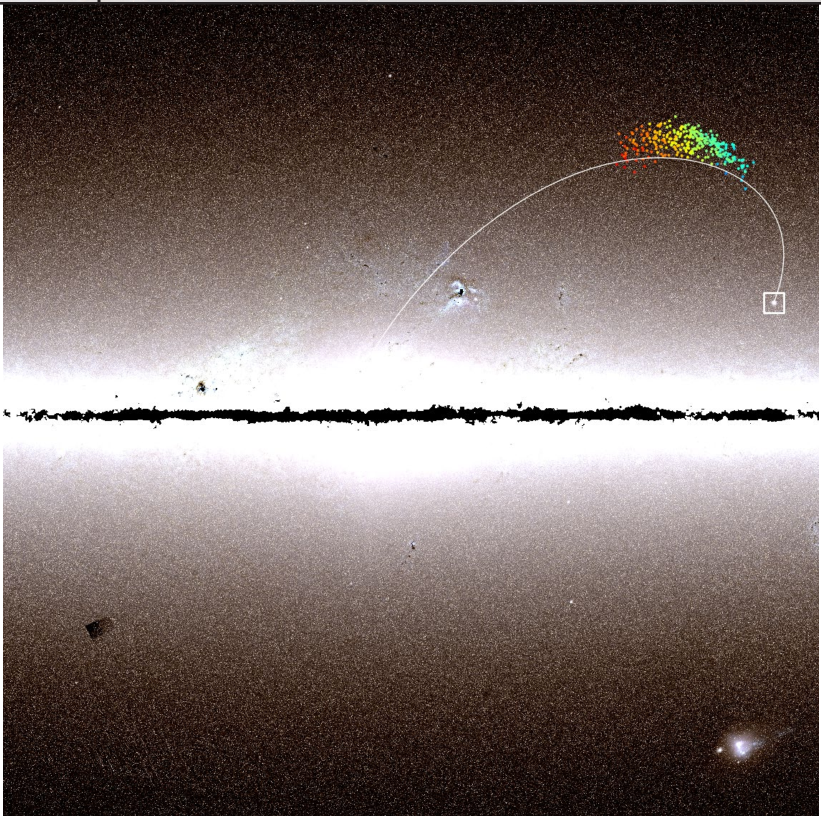


FIGURE 10.8

- This motion can also be used to derive the past orbital trajectory of Omega Centauri. The Gaia data have identified a trailing group of stars following this same trajectory with the same motion. These 309 stars are spread over a sky angle of 18° and are well separated from the cluster. Spectroscopic studies with ground-based telescopes show that these stars have heavy-element abundances similar to those in Omega Centauri. Thus, both the motions and abundances of the trailing stars indicate that they were once members of the cluster. It appears that these stars were tidally stripped from the globular by the gravity of the Milky Way.

READINGS

Frebel, *Searching for the Oldest Stars*.

Stevenson, *The Complex Lives of Star Clusters*.

Weintraub, *How Old Is the Universe?*

Young, "Spirits of Our Galaxy's Past."

QUESTIONS

1. When the orbit of a globular cluster takes it through the galactic disk, is it likely that there will be a large number of direct stellar collisions?

2. It has been suggested that Kapteyn's Star (a close neighbor of the Sun, at a distance of 13 light-years) was originally a member of the Omega Centauri cluster. What kind of evidence could support such a claim?

Lecture 11

SATELLITE GALAXIES: THE MAGELLANIC CLOUDS

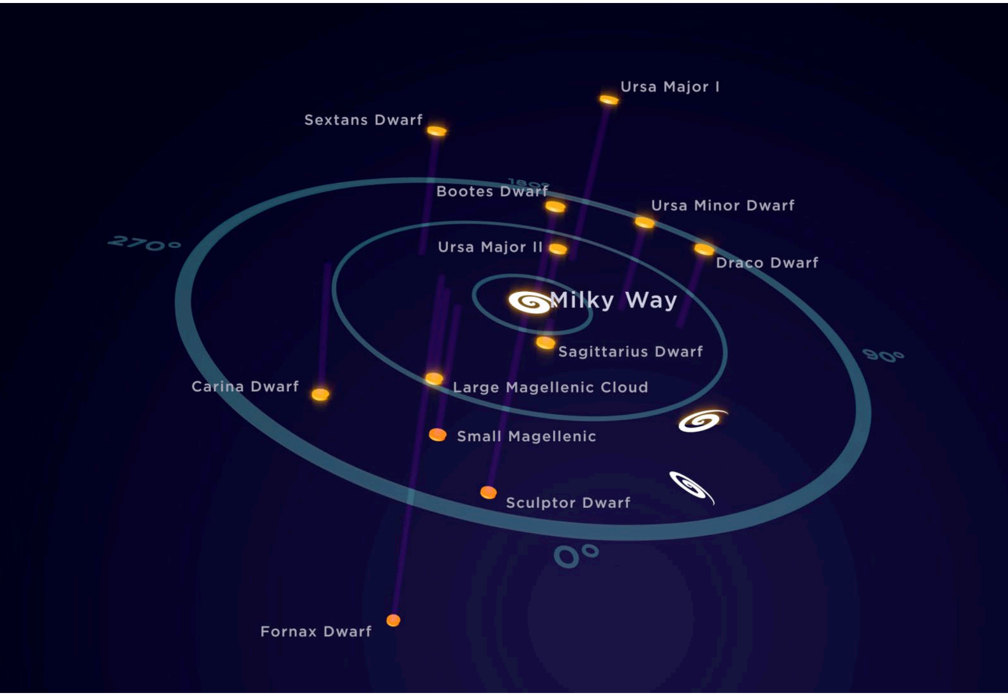
Beyond most of the globular star clusters in the galactic halo, there is a population of small satellite galaxies orbiting the Milky Way. Among these satellites, 2 are bright enough to be seen with the naked eye. They stand out as fuzzy patches of light in the dark southern sky near the brighter glow of the Milky Way. They have been known since antiquity by the indigenous peoples of the Southern Hemisphere; today, they are known as the Large and Small Magellanic* Clouds. Despite their appearance as clouds of light to the naked eye, the Magellanic Clouds are actually a pair of irregular dwarf galaxies.

* Portuguese explorer Ferdinand Magellan's expedition in the early 1500s was the first to sail around the world.

The Large and Small Magellanic Clouds

- More than 40 small galaxies have been identified to date as potential satellites of the Milky Way Galaxy. The positions of the most prominent dozen satellites are shown in this map [FIGURE 11.1]. Except for the Magellanic Clouds, all of these galaxies are gas-poor dwarf spheroidals or dwarf ellipticals consisting mostly of Population II stars. The smallest dwarf galaxies identified to date have thousands of stars and diameters less than 1000 light-years.

FIGURE 11.1



- Among the satellite galaxies of the Milky Way, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) [FIGURE 11.2] are the most massive, the most luminous, and the only 2 with significant amounts of interstellar matter and ongoing star formation. They are also among the nearest, with respective LMC and SMC distances of 160,000 and 200,000 light-years. Their angular separation of 21° on the sky corresponds to a physical separation of 75,000 light-years.

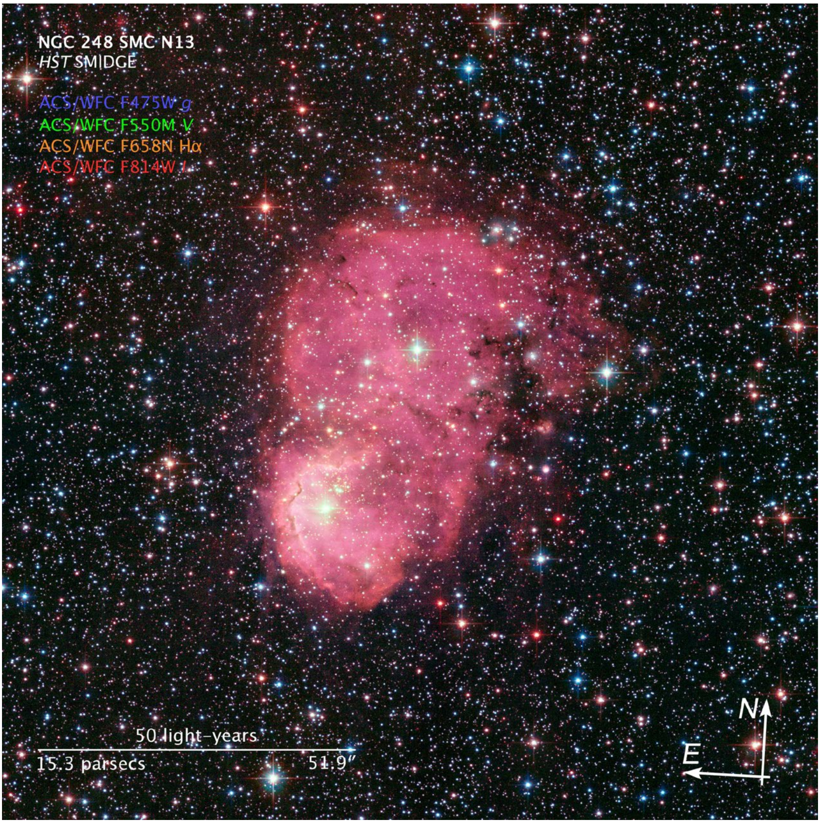
FIGURE 11.2

- The visual appearance of both galaxies appears irregular, but there are key differences. The LMC stars are mostly in a flat disk with a stellar bar and a single spiral arm. This unusual arrangement has led to the LMC often being classified as the prototypical barred Magellanic spiral.

- The smaller SMC also has a bar-like main body, but it appears more end-on as viewed from Earth. This bar is rich in interstellar gas and young stars, while the older stars show a more spherical distribution. We now know that the irregular shapes of the LMC and the SMC reflect their past gravitational interactions. These interactions continue to help drive the ongoing star formation in both galaxies. The resulting hot, young, massive stars excite the surrounding hydrogen gas to glow.

- NGC 248 is one of these emission nebulae in the SMC [FIGURE 11.3]. As viewed by Hubble, this nebula measures about 20 by 60 light-years, making it twice the size of the Orion Nebula, which is the brightest nebula in our night sky. The heavy-element abundances in NGC 248 and its associated young stars are about 20% that of the nebulae and young stars in the Milky Way. This comparison indicates that the long-term rate of star formation in the SMC, despite its current activity, has been appreciably slower than that in the Milky Way.

FIGURE 11.3



- Among the emission nebulae of the SMC, the most beautiful one lies on the outskirts of this galaxy. It encompasses the young star cluster NGC 602 [FIGURE 11.4] and its surrounding star formation region. The sharp Hubble image of this region has it all: a star cluster, a sculpted nebula, and background galaxies. This view is often voted as one of the top 10 Hubble images of all time.

FIGURE 11.4

- At the distance of NGC 602, the Hubble view is about 180 light-years across. The star cluster is inside the vast dust cavity, which spans about 100 light-years. The cluster is about 5 million years old, and its brightness is dominated by several hot, luminous blue stars. The star formation in this region has progressed from the inside out as the stars' ultraviolet radiation has eroded the surrounding dust. It is likely that the formation of this SMC cluster was triggered by a collision between a few gas clouds with somewhat lower densities than the typical molecular clouds in the Milky Way.

The Tarantula Nebula

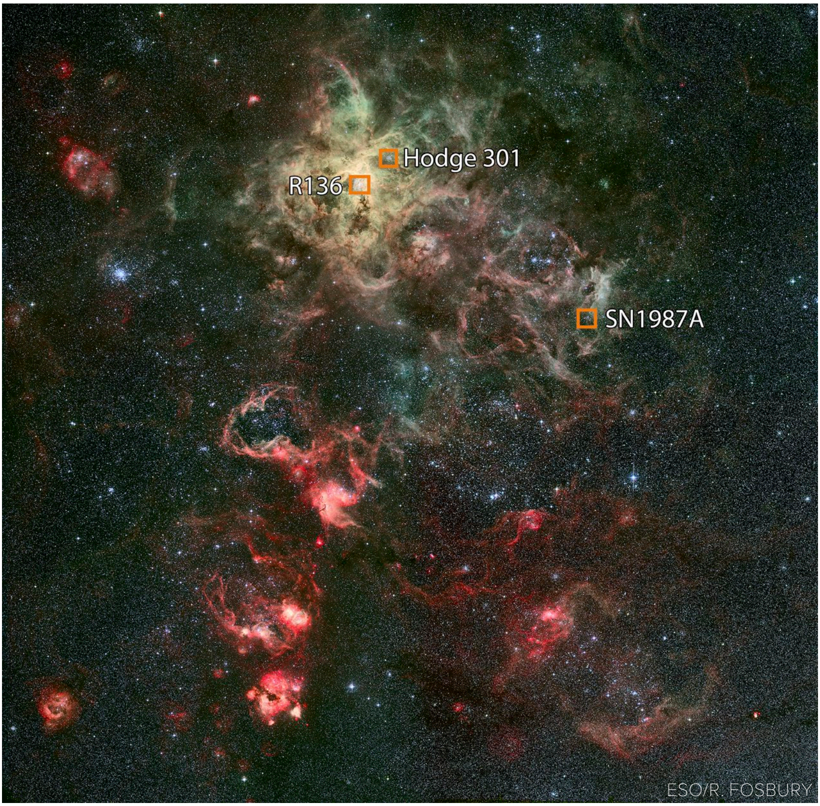
- In comparison to the SMC, a large-scale optical view of the LMC reveals a far greater number of emission nebulae associated with star formation activity [FIGURE 11.5]. Along with its larger size, the overall stellar mass of the LMC is also about 10 times greater than the SMC. The heavy-element abundances of its youngest stars are about 50% that of the nebulae and young stars in the Milky Way. This metallicity is consistent with a higher long-term star formation rate in the LMC than in the SMC.

FIGURE 11.5

- Nowhere in the local universe is the star formation rate currently higher than in the 30 Doradus region of the LMC. Despite its distance of 160,000 light-years, this bright patch of nebulosity is visible to the naked eye like a fuzzy star. It acquired its modern Tarantula Nebula name based on deep telescopic images, in which the nebular filaments collectively look like spider legs.

- This ground-based optical view of the Tarantula Nebula [FIGURE 11.6] is 1700 light-years across. Including its fainter regions, the nebula itself is about 1000 light-years in diameter. The brightest region of the nebula is associated with the young massive star cluster R136.

FIGURE 11.6

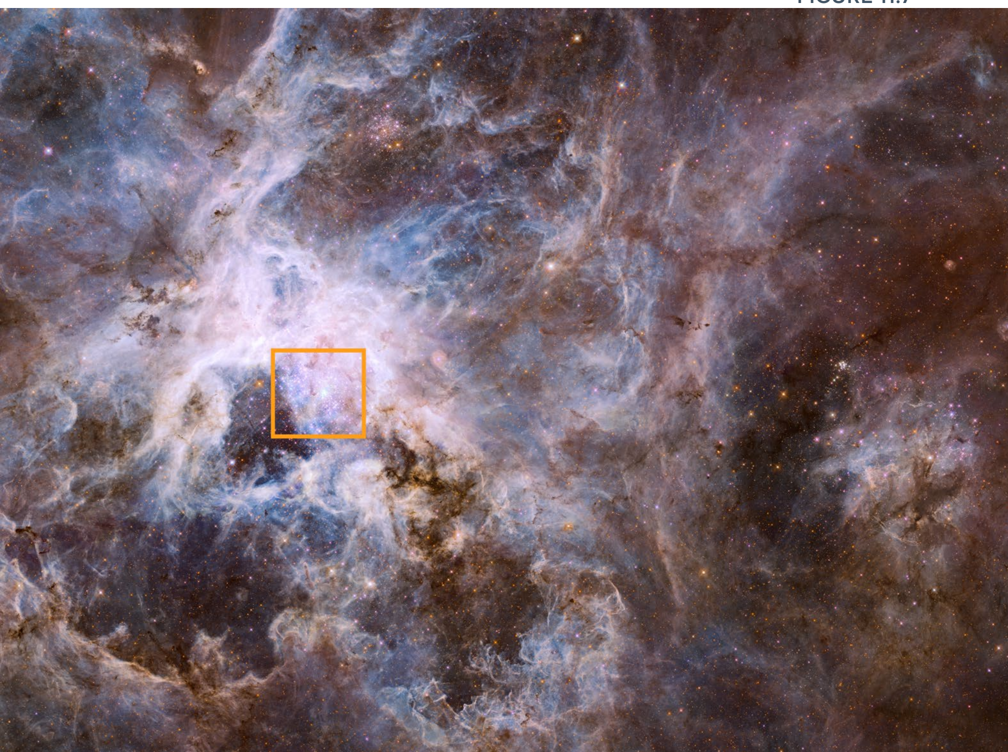


- The other major star cluster formed by the nebula is known as Hodge 301. It is located at a distance of 150 light-years from R136. The Tarantula Nebula is also the home of Supernova 1987A, a Type II supernova that exploded in 1987. The remnant of this explosion is located on the fainter outskirts of the nebula, far from the 2 star clusters.

- This detailed Hubble view of the brighter ½ of the Tarantula Nebula [FIGURE 11.7] spans 550 light-years. The R136 star cluster is located left of center. The sky width of this image is equal to 40% of the Moon's diameter. It is a mosaic of 30 overlapping star fields observed with the Advanced Camera for Surveys and Wide Field Camera 3.

- The resulting image is a sum of 700 exposures spanning 100 hours covering 5 wavelength regions. This wavelength coverage from the ultraviolet to the near-infrared is visually displayed in the image with colors ranging from blue to orange. The relative brightness of the nebular regions reflects the intensity of their hydrogen emission.

FIGURE 11.7



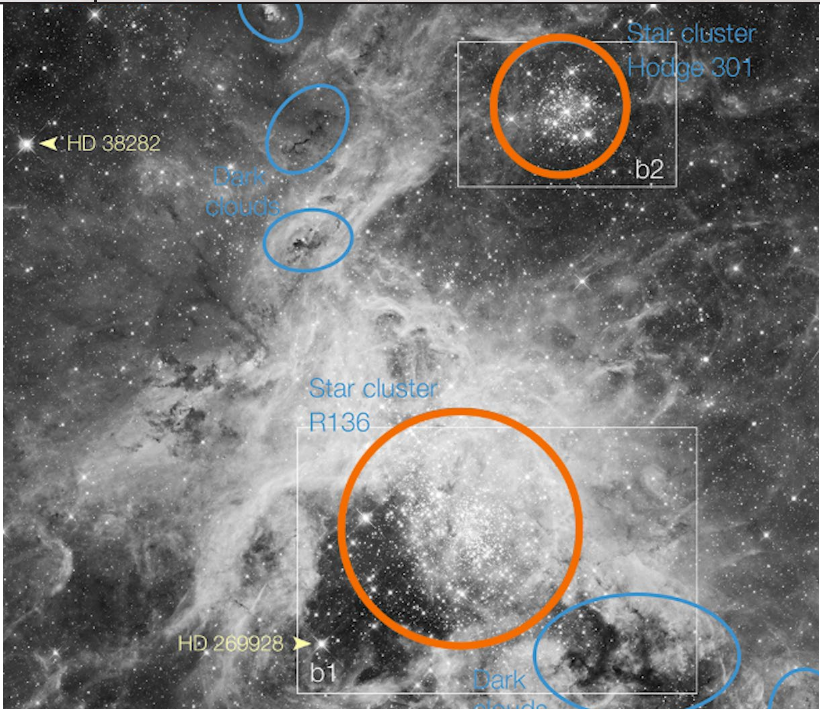


FIGURE 11.8

- The complex gas structure on a variety of length scales reflects multiple epochs and stages of recent star formation in the nebula. On the largest scales, several superbubbles, with diameters ranging from 50 to 100 light-years, are apparent. Such structures likely took millions of years to develop from the stellar winds and supernova explosions of multiple massive stars. On the smallest scales, newborn stars can be seen emerging from filamentary dark clouds.

- This 250-light-year-wide region around R136 and Hodge 301 [FIGURE 11.8] shows that these 2 most prominent star clusters are on the edge of or inside superbubbles in the ionized nebular gas. The other circled features in this close-up include some of the dusty dark clouds in the region. The topmost of these clouds shows new stars forming.

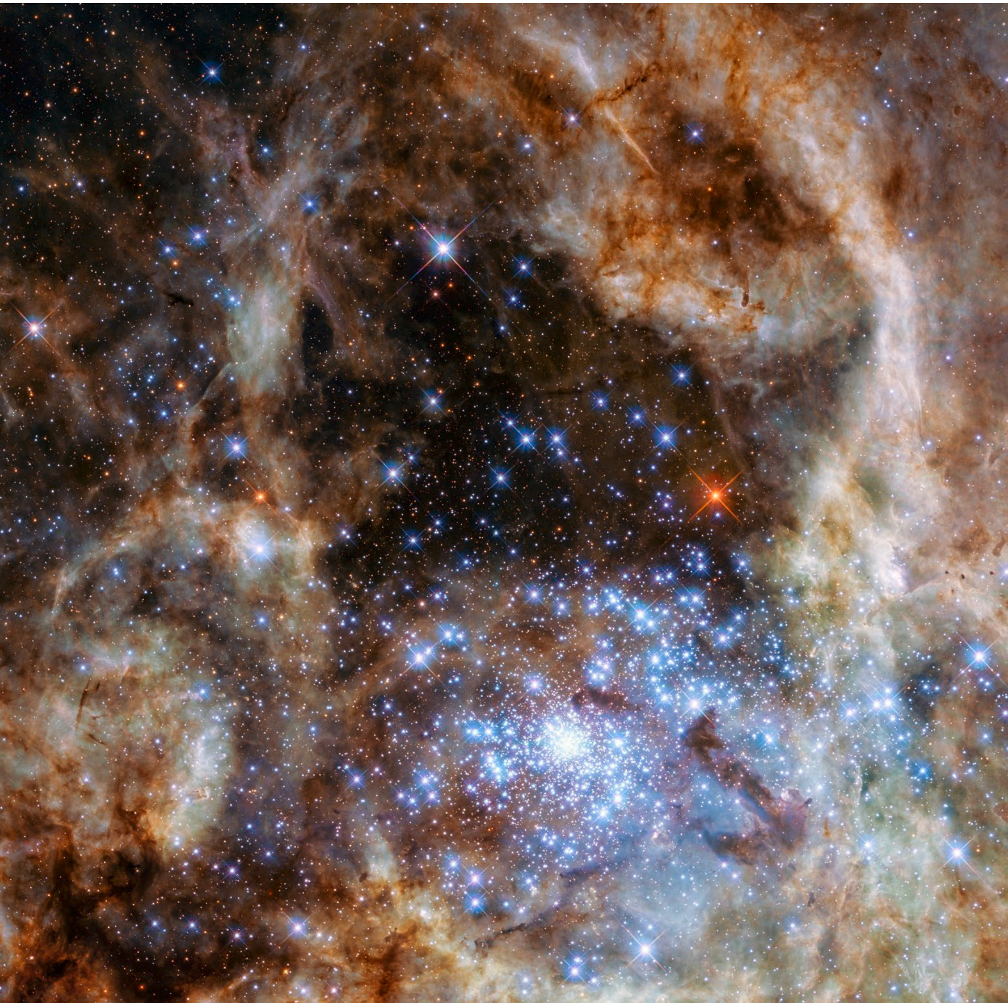
- The Hodge 301 cluster has a diameter of about 20 light-years and a total stellar mass of 10,000 Suns. Based on its HR diagram, the cluster is about 25 million years old. This age makes Hodge 301 [FIGURE 11.9] the oldest of the star clusters in the Tarantula Nebula. It also indicates that the epoch of star formation in the nebula began about 25 million years ago. Given the mass and age of Hodge 301, about 40 of its stars have exploded as supernovas since that time.

FIGURE 11.9

It is possible that the evolution of the Hodge 301 star cluster may have led to the formation of the R136 cluster millions of years later.

- This Hubble view of the R136 cluster region [FIGURE 11.10] measures 120 light-years across. The R136 designation refers to the innermost 7 light-years of the cluster, where its brightest, most massive stars are heavily concentrated. The stars in this region have a total mass of 100,000 Suns. It is the radiation from these stars that is mostly responsible for the glow of the Tarantula Nebula. The entire cluster has a diameter of about 50 light-years and a mass of 500,000 Suns and is often referred to as NGC 2070.

FIGURE 11.10



- The existence of massive, luminous stars in the R136 cluster tells us that it is very young. In fact, the R136 cluster is so young that none of its massive stars have exploded as supernovas yet. Thus, the nebular gas cavity that is already beginning to form around R136 is driven entirely by stellar winds.

- The Tarantula Nebula's star formation started 25 million years ago with the Hodge 301 cluster and is now focused on the R136 starburst.

With its mass of 265 solar masses, the star named R136a1 is currently the most massive star known in the universe. The diameter of R136a1 is more than 30 times that of the Sun. It is so luminous that it alone is responsible for 7% of the Tarantula Nebula's glow.

FIGURE 11.12

Galactic Interactions

- Observations far beyond the Milky Way have revealed that starbursts and young globular clusters are typically associated with interacting galaxies. There is strong evidence that the LMC has been shaped by gravitational interactions with the SMC. A key clue in this regard is the irregular appearance of the LMC amid some spiral characteristics.

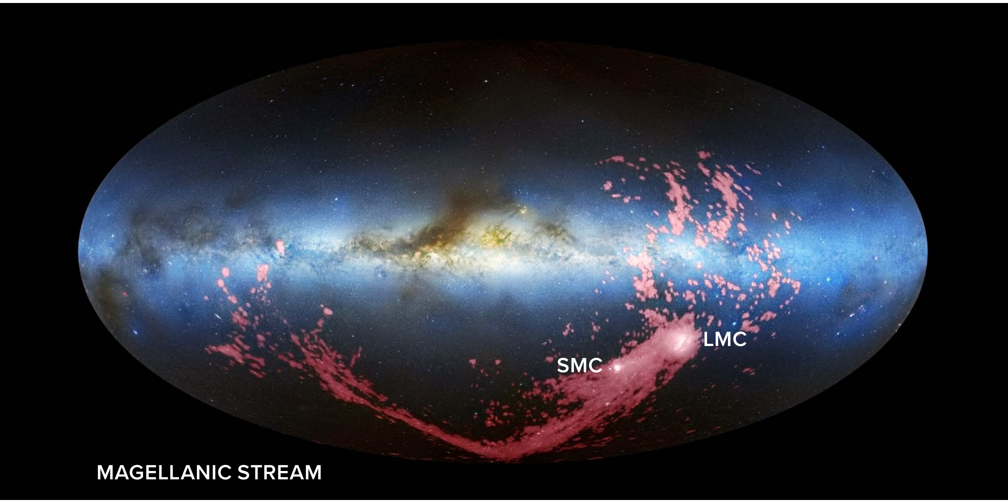
- Through a number of Hubble images taken over the years, the motions of hundreds of LMC stars are now known. Based on these motions, it is possible to show that the entire LMC is rotating with a period of 250 million years. Such rotation is expected if the LMC was originally a barred spiral disk galaxy. The disruption of its spiral arms is the most obvious evidence of a gravitational interaction with another galaxy. However, there is no optical connection evident between the LMC and the SMC over their separation of 75,000 light-years.

- Nevertheless, observations at radio wavelengths have shown that these 2 galaxies are linked by a bridge of atomic hydrogen gas. The amount of hydrogen in this so-called Magellanic Bridge comes to a staggering total of 200 million solar masses! Based on the low metallicity of this gas, most of it must have come from the SMC. The simplest interpretation is that the more massive LMC has tidally stripped the SMC of much of its gas for billions of years as they orbit each other. These interactions have also led to the current irregular stellar appearance of both galaxies.

- On a larger scale, radio observations have revealed that the Magellanic Cloud interactions are a source of hydrogen gas that stretches over ½ the sky. This so-called Magellanic Stream [FIGURE 11.13] consists of 300 million solar masses of atomic hydrogen gas. If we account for all of the gas in this stream and in the Magellanic Bridge, the resulting amount is more than twice that of the gas currently in both galaxies combined. In other words, the SMC and the LMC used to be far more gas-rich than they are now.

- The Magellanic Stream is the only known gaseous tidal stream around the Milky Way. It is unlike the stellar streams that are tidally stripped from gas-poor dwarf satellite galaxies by the Milky Way.

FIGURE 11.13



MAGELLANIC STREAM

- Beyond its source in the Magellanic Clouds, the dynamical origin of the Magellanic Stream is uncertain. Most models originally interpreted it as arising from the tidal stripping of the Magellanic Clouds by the Milky Way. Based on recent data, the latest models have focused on interactions between the LMC and the SMC. In these models, the 2 galaxies have either completed 1 orbit around the Milky Way or are on their first close pass. Prior to this time, they have been orbiting each other for billions of years.

- A popular computer simulation begins 1 billion years ago with the LMC and the SMC nearly hitting each other at a distance of 770,000 light-years from the Milky Way. After the original near hit, the 2 galaxies separated and then collided again 100 million years ago at a distance of 160,000 light-years. As a result, they generated tidal gas trails that stretch far from the galaxies—a close match to the observed Magellanic Stream.

- A recent collision between the Magellanic Clouds would also explain their irregular appearance. In addition, such a collision would generate cloud-on-cloud collisions within these galaxies. The resulting large-scale bursts of star formation could have eventually led to the Tarantula Nebula and its massive R136 star cluster in the LMC. It could also explain why the young massive star clusters in the LMC typically have higher masses and core densities than those in the Milky Way. Billions of years from now, the gravitational dance between the Magellanic Clouds will end with them merging with each other and then the Milky Way.

Irregular dwarf galaxies like the Magellanic Clouds are similar to the small gas-rich galaxies that originally built the Milky Way through mergers and collisions more than 12 billion years ago.

READINGS

D'Onghia and Fox, "The Magellanic Stream."
Portegies Zwart, McMillan, and Gieles, "Young Massive Star Clusters."
Sobel, *The Glass Universe*.
Van Den Bergh, *The Galaxies of the Local Group*.

QUESTIONS

1. Is it likely that one of the massive stars currently seen in the R136 cluster has already exploded as a supernova whose light has yet to reach Earth?

2. Is it possible that a collision of 2 gas-poor dwarf elliptical galaxies could generate a starburst?

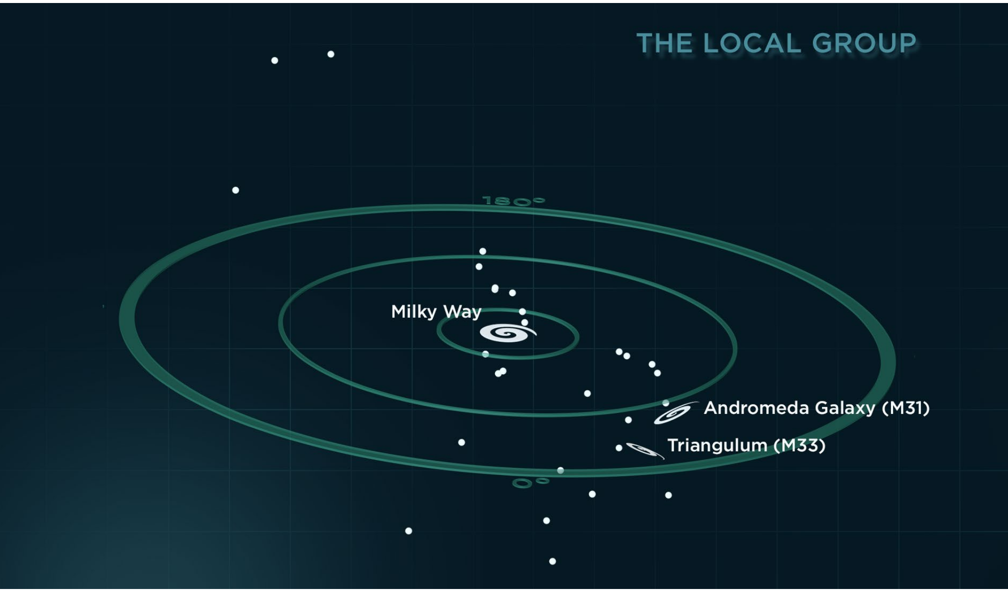
THE FUTURE OF THE MILKY WAY

The Andromeda Galaxy, the nearest spiral galaxy to the Milky Way, is moving toward us at a speed that's more than 100 times faster than a rifle bullet. Fortunately, that's only 0.04% of the speed of light, and it will take quite a while to get here since it's 2.5 million light-years away. Nevertheless, as a result of this collision and subsequent merger, the shape and character of the Milky Way will dramatically change over the course of a few billion years.

Spirals in the Galactic Neighborhood

- The 2 closest spirals to the Milky Way are Andromeda, also known as M31, and the Triangulum Galaxy, also known as M33. These 3 spirals are the largest galaxies in a galaxy cluster that was named the Local Group by Edwin Hubble.

FIGURE 12.1



- Most of the 60 galaxies in the Local Group are dwarf satellites of the Milky Way and M31. These 2 spirals are by far the 2 most massive galaxies in the Local Group. The Milky Way, M31, and M33 are all within 3 million light-years of each other. Overall, the Local Group has a radius of about 5 million light-years. The galaxies in clusters like the Local Group are held together by their mutual gravity.

Galaxies are typically found in clusters, with memberships ranging from a few to thousands of galaxies.

- Beyond the Local Group, the nearest galaxy clusters are at a distance of about 10 million light-years. In our expanding big bang universe, it is the space between galaxy clusters that is expanding. Within a galaxy cluster or group, the mutual gravity of their constituent galaxies is strong enough to resist this expansion. At the same time, as the galaxies in a cluster orbit their collective center of mass, close interactions and occasional collisions between the galaxies are inevitable.

- From our perspective on Earth inside the Milky Way, M31 and M33 are close together on the sky. They are separated by a sky angle of 14, or about 28 Moon widths. Given the distances of 2.5 and 2.8 million light-years to M31 and M33, this angle corresponds to a physical separation of 700,000 light-years.

- Both galaxies appear to the naked eye as faint, fuzzy objects, even when viewed under optimal sky conditions at a dark location. A well-equipped camera can improve this view to clearly show that Andromeda is much larger than M33. Specifically, the spiral disks of M31 and M33 have respective diameters of about 200,000 and 60,000 light-years.

- Due to their proximity, M31 and M33 are 2 of the most well-studied spiral galaxies. In particular, Hubble has invested a lot of observing time into imaging them in detail.

- The Triangulum Galaxy's disk is inclined by an angle of 54°, which provides a view mostly unobscured by dust. The spiral structure of M33 is loosely defined by the many pink hydrogen nebulae excited by hot stars in their vicinity. Unlike the Milky Way, there is no obvious evidence of a stellar bar at the center of this spiral. It also has a smaller stellar core, with an upper limit of 3000 solar masses on any supermassive black hole at the nucleus.

- Hubble has taken an enormous 665-megapixel image of the central ⅓ of M33 [FIGURE 12.2]. It involves a mosaic of 54 separate Hubble star fields and 40 hours of observation time. About 15 billion of M33's 40 billion stars are visible in this image. Overall, M33 has about 10% of the number of stars and 5% of the total mass of the Milky Way.*

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* The current star formation rate in M33 is the equivalent of 1 solar mass star every 2 years. In comparison, the current Milky Way rate is twice as fast, with 1 solar mass star every year, and the current rate in Andromeda is the equivalent of 1 solar mass star every 3 years.

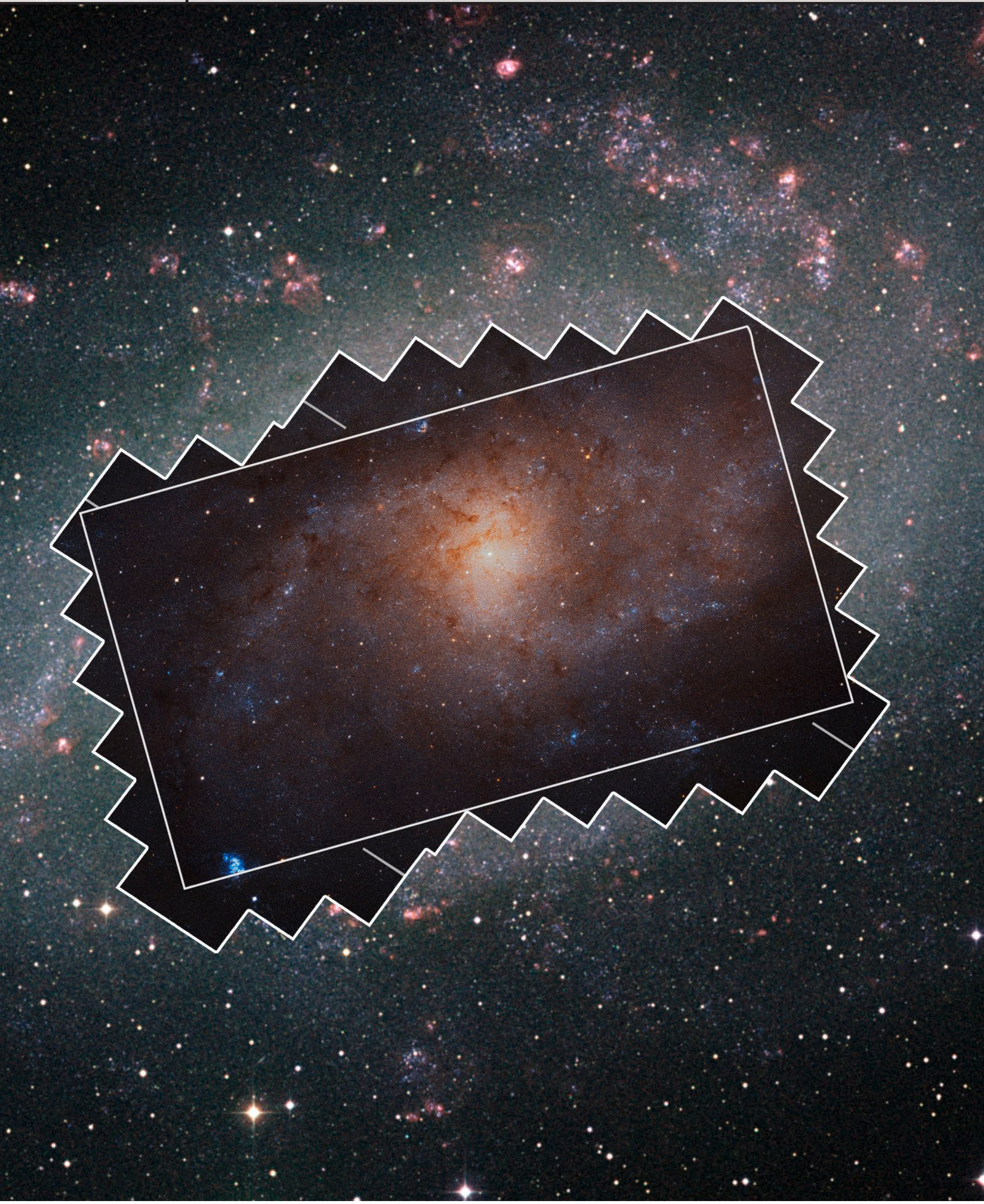


FIGURE 12.2

- The Andromeda Galaxy has a much larger nucleus and a greater inclination than M33. The spiral arms of Andromeda also appear to be wound more tightly than those in M33. This spiral structure is most evident in the dust lanes and the brightest blue stars.

- Hubble's gigantic image of Andromeda [FIGURE 12.3] is an astonishing 3.9 billion pixels in size and covers ⅓ of the galaxy's disk. It stretches more than 60 million light-years from the core of Andromeda to its outer spiral arms. It involves a mosaic of 7400 exposures linking 411 separate Hubble star fields. It is the largest Hubble image ever assembled of any contiguous part of the sky.

FIGURE 12.3

- Indeed, it covers a sky area that is almost 3 Moons across. Overall, Andromeda is about twice the size of the Milky Way and has about 3 times as many stars. More than 100 million of those stars and thousands of star clusters are in the Hubble image.

- This section of the Andromeda image [FIGURE 12.4] stretches across 40,000 light-years. The large yellow region of the nuclear bulge is filled with the light of many millions of Population II stars. There is strong evidence that a black hole with the mass of 100 million Suns resides at the center of this bulge.†

FIGURE 12.4

- Another feature of this large-scale Hubble view is the prominent spiral arm that circles from the top left to the lower right. The bright blue stars, star clusters, and associated dust patches clearly stand out across the long stretch of this spiral arm.

- A close-up that spans 4200 light-years features the lower part of this spiral arm [FIGURE 12.5]. The younger blue stars associated with the spiral arm stretch diagonally across the image from the upper left to the lower right. Some of the dust lanes, open star clusters, and star-forming regions making up this arm are labeled accordingly.

- Moving away from the spiral arm toward the upper right of the image, we see more exclusively the older, redder stars that are predominant in the disk of Andromeda. In this less dusty region, we also see distant spiral galaxies far beyond the stars of Andromeda.

† The large size of Andromeda's nuclear bulge is consistent with it having a central supermassive black hole that is 25 times more massive than the one at the core of the Milky Way.

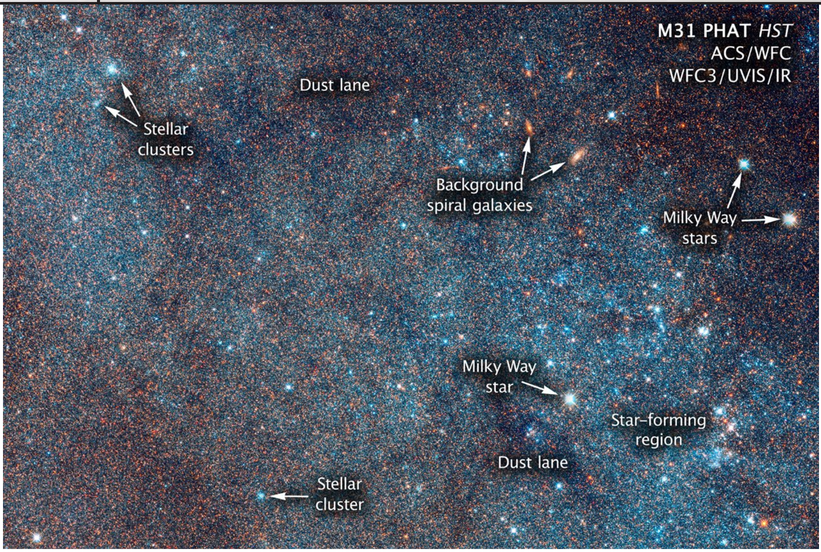


FIGURE 12.5

The Hubble image of Andromeda is unprecedented in elucidating such fine details over a vast region of a large spiral galaxy.

Future Interactions

- Considered in isolation or with families of small satellite galaxies, large spirals like Andromeda and the Milky Way would be expected to maintain their spiral structure and continue to produce new generations of stars in their gas-rich disks for many billions of years. However, such galaxies are so massive that they can dramatically impact each other's structure and evolution if they pass within a few hundred thousand light-years of each other during their gravitational dance in a galaxy cluster.

- Based on spectroscopic measurements of Andromeda, it has been known for some time that the center of this galaxy is moving toward the center of the Milky Way at a velocity of 120 km/s.

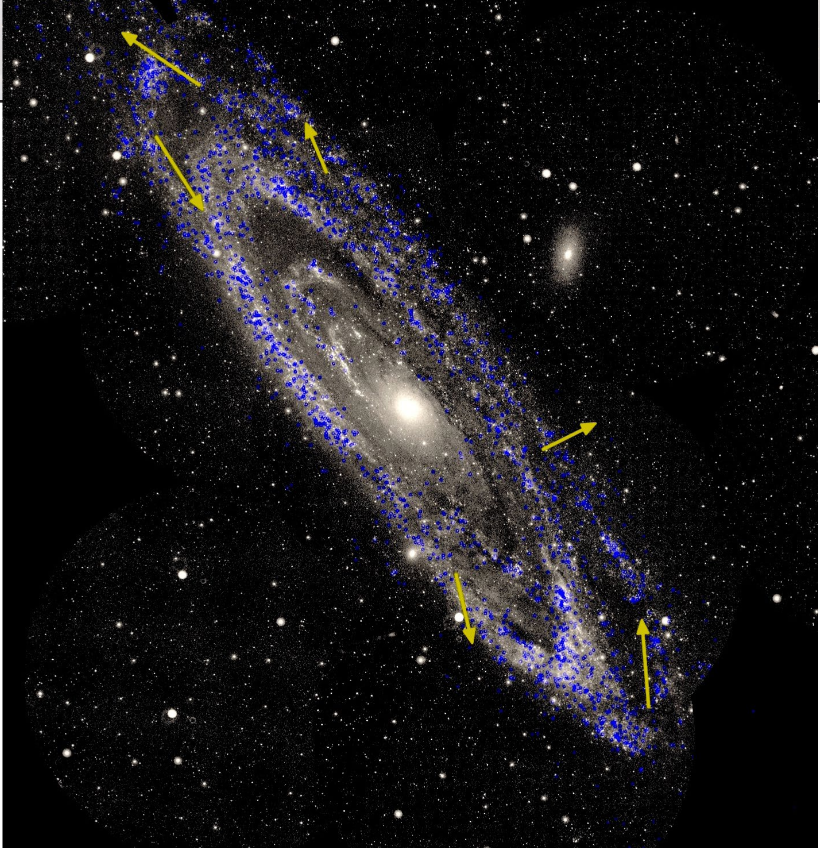


FIGURE 12.6

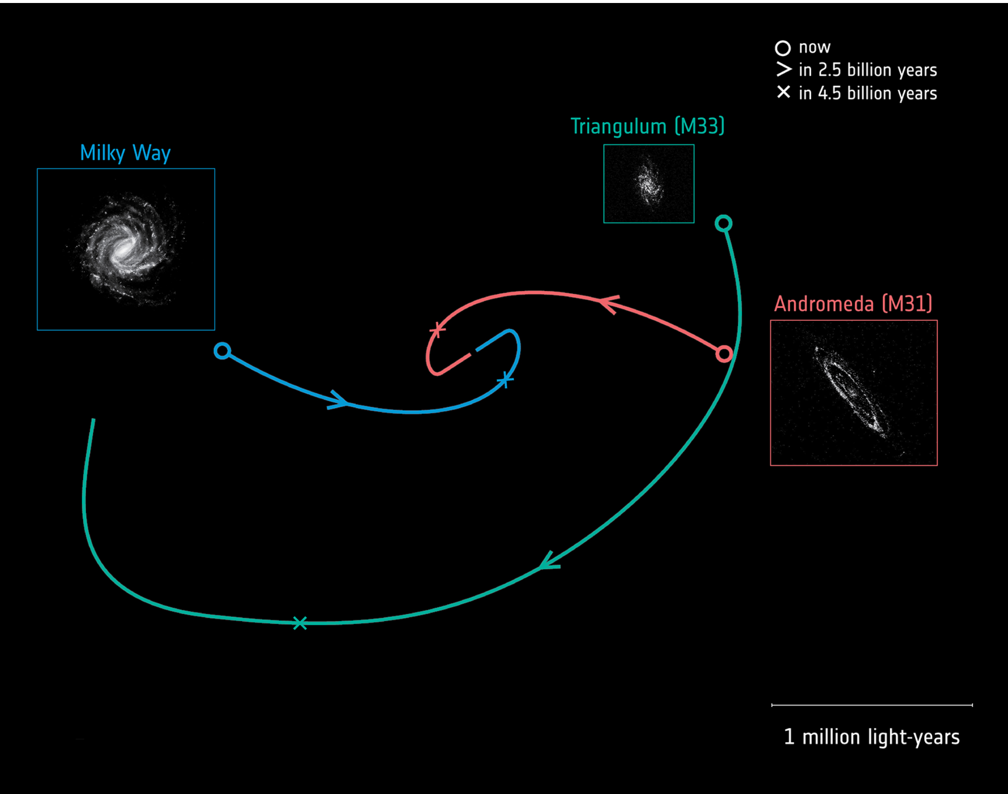
- A key unknown has been the tangential motion of Andromeda across our line of sight on the sky. If this motion is actually larger than its motion directly toward us, then Andromeda will not be coming close to the Milky Way for a very, very long time. On the other hand, if its sky motion is small, Andromeda and the Milky Way will suffer a near miss or a direct hit in about 4 to 5 billion years. The key challenge in determining the correct scenario is actually measuring the tiny sky motions of Andromeda's stars at its distance of 2.5 million light-years.

- The Gaia observatory has succeeded in measuring the sky motions of 1000 luminous stars in the Andromeda Galaxy [FIGURE 12.6]. Combined with earlier images of Andromeda taken with Hubble, the Gaia data has made it possible to better separate the motion due to the galaxy's rotation from the motion of the galaxy itself. The resulting tangential velocity of 60 km/s is about ½ of Andromeda's motion directly toward the Milky Way. A smaller value obtained earlier with the Hubble data alone had shown that the 2 spirals would pass within 100,000 light-years of each other in about 3.9 billion years.

- The new Gaia forecast updates the expected motions of the 3 spiral galaxies in the Local Group over the next 6 billion years [FIGURE 12.7]. It shows that Andromeda and the Milky Way will pass within 400,000 light-years of each other in about 4.5 billion years. The 2 galaxies will then separate a bit more and begin a gravitational dance that brings them closer and closer together.

- In the case of M33, Gaia has been able to clock its rotation and sky motion based on 1500 of its most luminous stars. In 4.5 billion years, M33 is projected to move to an orbital position of 1.6 million light-years away from the other 2 spirals.

FIGURE 12.7



The Milky Way–Andromeda Merger

- In about 4 billion years, Andromeda will be nearing its first close pass of the Milky Way. As a result, it will be a huge feature on the night sky [FIGURE 12.8], rivaling the entire Milky Way in brightness. At this point in time, the spiral structure of both galaxies will not yet have been affected much by their gravitational interaction.

FIGURE 12.8

- As Andromeda and the Milky Way pass each other over the following billion years, their gravitational attraction will begin to pull tidal tails of stars and gas out of both galaxies. At this stage, they will look something like the pair of distorted interacting spirals known as Arp 273 [FIGURE 12.9]. This beautiful rose-shaped pair of galaxies is located in the constellation Andromeda at a distance of 300 million light-years. The larger galaxy is about 5 times more massive than the smaller one.

FIGURE 12.9

- The distorted appearance of the spirals in both galaxies indicates that they recently suffered a close pass. The Hubble image of the interacting Arp 273 galaxies is thus a snapshot in time of an initial close pass that has been playing out for hundreds of millions of years.

- At a similar stage, the Milky Way and Andromeda will provide a somewhat comparable view from afar. Some differences may arise from their smaller mass ratio and more distant first pass.

The collision of the Andromeda Galaxy with the Milky Way will be a transformative event that changes the very essence of our night sky.

- As viewed from Earth after this first pass [FIGURE 12.10], the resulting night sky is likely to feature a warped Milky Way studded with blue bursts of star formation. The gas and stars in Andromeda will be tidally stretched across the sky with ongoing starbursts throughout. At about the same time, the Sun will have begun its expansion to a red giant star.

- A common feature generated by the first close pass of 2 large spirals are tidal tails of gas and stars. As the clouds of gas in these tails collide with one another, they can produce bursts of star formation. By the time of a more direct hit in the second pass, the galaxy cores are typically surrounded by a bright starburst.

FIGURE 12.10

FIGURE 12.11

- The NGC 2623 pair of galaxies is in such an interaction stage [FIGURE 12.11]. Its Hubble view is what the Milky Way and Andromeda should look like from afar in about 6 billion years. NGC 2623‡ is located in the constellation Cancer at a distance of about 250 million light-years. The Hubble image is 240,000 light-years across at this distance, with each tidal tail stretching 80,000 light-years. This image is the sum of multiple exposures spanning 2.8 hours of observing time. Its blue-to-red color scheme reflects multiwavelength observations taken from the blue to the near-infrared.

- Zooming into the innermost 60,000 light-years of this image, we see the nuclei of the 2 original galaxies beginning to merge in the center. They are surrounded by many bright blue star clusters that extend into the tidal tails. It turns out that the overall star formation rate in this galaxy merger is about 20 times that of the Milky Way. Induced by many cloud collisions, this starburst is rapidly converting the remaining gas in these galaxies into stars.

‡ The odd-shaped object NGC 2623 is the result of a collision and ongoing merger of 2 spiral galaxies.

- A classic example of a collision starburst is a galaxy pair known as the Antennae Galaxies [FIGURE 12.12]. They are located in the southern constellation Corvus at a distance of 70 million light-years. Hubble has imaged the innermost 60,000 light-years of the Antennae at its highest resolution. It reveals the old yellow cores of 2 spiral galaxies amid a tangle of bright blue star clusters, pink hydrogen nebulae, and brown dust clouds. Among the 1000 massive young star clusters identified in this image, about 100 are compact enough to eventually become globular clusters. Like the previous example, the overall Antennae star formation rate is also about 20 times that of the Milky Way.

FIGURE 12.12

FIGURE 12.13

- Based on these 2 cases, the entire night sky as viewed from Earth in about 6 billion years [FIGURE 12.13] will look like the best fireworks display, and it will last for many millions of years. As Andromeda and the Milky Way collide directly, it will take that long for their gas to be consumed by the resulting starburst. Locally, the Sun will be evolving from a red giant to a white dwarf. Given the vast star spacing in the 2 galaxies, it is very unlikely that the planetary orbits in the solar system will be disrupted by their collision.

- The Milky Way–Andromeda merger finalizes in about 8 billion years, with the product looking like an elliptical galaxy.

- But what will be the fate of the solar system as a result of this merger? There is about a 10% chance that it will be thrown on a tidal tail into extragalactic space. It is less likely that it will be thrown near or into the merged supermassive black hole at the new galactic center. Due to the vast space between the stars, there is essentially no chance that it will collide with a star from Andromeda. Thus, most likely, it will be thrown into a large elliptical orbit around the new galactic center.

- Imagine the night-sky view on Earth from such a future solar system in about 10 billion years [FIGURE 12.14]. The diffuse band of light across the sky from which the Milky Way got its name is now gone. Instead, there is a bright glow in one part of the sky toward the new galactic center. A few billion years after this time, there will be some brief, minor excitement when M33 merges with the now-established Milkomeda§ galaxy. Otherwise, this will be the nighttime view on Earth for the next 100 billion years, until the tiniest stars burn out.

FIGURE 12.14

§ Now that the future of the Milky Way and Andromeda is clearer, names like Milkomeda have been proposed for the merged elliptical that it is destined to become.

READINGS

Christensen, De Martin, and Shida, *Cosmic Collisions*.
Stevenson, *The Complex Lives of Star Clusters.*
Struck, *Galaxy Collisions*.
Van Den Bergh, *The Galaxies of the Local Group*.

QUESTIONS

1 Why were galaxy collisions more frequent long ago in the universe? Are spirals or ellipticals more likely to constitute the majority of large galaxies in rich clusters of galaxies?

2 Among the Hubble Space Telescope images in this course, which one will likely have the longest-lasting impact?

QUIZ

1 What is the distance between the Bubble Nebula and the Andromeda Galaxy?

a 250 light-years
b 2500 light-years
c 25,000 light-years
d 250,000 light-years
e 2,500,000 light-years

2 The 2 basic types of spiral galaxies are classified according to which of the following?

a whether they are viewed face-on or edge-on
b whether or not they have a stellar bar in their centers
c whether or not they have a halo of globular star clusters
d whether or not they have a central black hole
e whether or not they have ongoing star formation

3 What is the approximate distance between the Earth and the Sun?

a 1 astronomical unit
b 500 light-seconds
c 1.5 million kilometers
d A and B
e all of the above

4 Which of the following is true of a typical bright comet as viewed from the Earth's surface?

a It can be tracked across the night sky for more than a year with the naked eye.
b It has a tail length equal to the distance between Jupiter and the Sun.
c It has a tail that points away from the Sun.
d A and B
e all of the above

5 Compared to an optical photon, an ultraviolet photon has which of the following?

a a higher energy
b a shorter wavelength
c a higher velocity
d A and B
e all of the above

6 The interstellar reddening effect produced by an intervening interstellar cloud on the color of background stars is due to which of the following?

a the cloud's dust
b the cloud's atomic gas
c the cloud's molecular gas
d the cloud's ionized gas
e none of the above

7 A Herbig-Haro object typically involves which of the following?

a gaseous patches of nebulosity
b a newborn star
c outflowing stellar jets of gas
d A and B
e all of the above

8 Herbig-Haro objects are commonly found in which of the following?

a the stellar halo of the Milky Way Galaxy
b star-forming molecular clouds associated with the Milky Way's spiral arms
c elliptical galaxies
d A and B
e all of the above

9 Main-sequence stars of spectral type B are typically __________ than those of spectral type A.

a cooler
b redder
c less massive
d longer-lived
e more luminous

10 Five million years from now, the stars in Westerlund 2 will include which of the following?

a supergiants
b red giants
c white dwarfs
d A and B
e all of the above

11 Over the course of its evolution, what will the Sun eventually become?

a a red giant
b a planetary nebula
c a supernova
d A and B
e all of the above

12 The mass-losing star at the heart of the Bubble Nebula is which of the following?

a a red giant
b a white dwarf
c a Wolf-Rayet star
d a solar-type star
e a red supergiant

13 The light echo around RS Puppis is produced by which of the following interstellar substances?

a diamonds
b atomic gas
c dust grains
d molecular gas
e none of the above

14 Cepheid A and Cepheid B have the same pulsation period. Cepheid A is at a distance of 1000 light-years. As viewed from Earth, Cepheid A is 4 times as bright as Cepheid B. Neglecting any dimming effects due to interstellar dust, what is the distance to Cepheid B?

a 250 light-years
b 500 light-years
c 1000 light-years
d 2000 light-years
e 4000 light-years

15 In the hours before a star explodes as a Type II supernova, its core consists mostly of which of the following?

a helium
b carbon
c silicon
d iron
e uranium

16 Imagine that the people of Earth observe a supernova explosion at a distance of 200 light-years in the year 2050. Forty years later, we receive a radio alert about the supernova from an extraterrestrial civilization on a planet whose sky position is directly opposite that of the supernova from our perspective on Earth. This planet must be at a distance of ___________ light-years from Earth.

a 20
b 40
c 80
d 100
e 200

17 None of the Population II main-sequence stars in the Milky Way have a spectral type of ___________.

a A
b B
c O
d A and B
e all of the above

18 A 4-million-solar-mass black hole has an event horizon that is about 20% of the diameter of ___________ orbit around the Sun.

a Mercury's
b Earth's
c Jupiter's
d Saturn's
e Neptune's

19 Compared to an open star cluster in the galactic disk, a globular star cluster in the galactic halo has which of the following?

a more stars
b older stars
c stars with lower abundances of heavy elements
d A and B
e all of the above

20 Due to the frequent gravitational interactions between the closely packed stars in globular clusters, which of the following is true?

a Younger-looking stars called blue stragglers can form.
b The higher-mass stars tend to sink inward toward the cluster cores.
c All of the Milky Way's globulars have become core-collapse clusters.
d A and B
e all of the above

21 The most massive star known is located where?

a Milky Way Galaxy
b Andromeda Galaxy
c Large Magellanic Cloud
d Small Magellanic Cloud
e Fornax dwarf galaxy

22 The evidence that the Large and Small Magellanic Clouds are a pair of interacting dwarf galaxies includes which of the following?

a the irregular morphology of their stars and nebulae at optical wavelengths
b the Magellanic Bridge of atomic hydrogen gas at radio wavelengths
c the Magellanic Stream of atomic hydrogen gas at radio wavelengths
d A and B
e all of the above

23 The space occupied by a __________ does not expand as the universe expands.

- a star cluster
- b galaxy
- c cluster of galaxies
- d A and B
- e all of the above

24 Ten billion years from now, the black hole at the center of the new Milkomeda Galaxy will have an event horizon that is about twice the diameter of __________ current orbit around the Sun.

- a Mercury's
- b Earth's
- c Jupiter's
- d Saturn's
- e Neptune's

ANSWER KEY

1 e; **2** b; **3** d; **4** c; **5** d; **6** a; **7** e; **8** b; **9** e; **10** a; **11** d; **12** c; **13** c; **14** d; **15** d; **16** a; **17** e; **18** a; **19** e; **20** d; **21** c; **22** e; **23** e; **24** b

BIBLIOGRAPHY

Bally, John, and Bo Reipurth. *The Birth of Stars and Planets.* Cambridge, UK: Cambridge University Press, 2006. An excellent, well-illustrated introduction to the process of star and planet formation.

Bartusiak, Marcia. *Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled On by Hawking Became Loved.* New Haven, CT: Yale University Press, 2015. A well-written introduction to the history and science of black holes.

———. *The Day We Found the Universe*. New York: Pantheon Books, 2009. A wonderful, well-researched history of the scientific efforts of Edwin Hubble, Henrietta Leavitt, Vesto Slipher, and others that led to the recognition of spiral nebulae as distant galaxies and the discovery of the expanding universe.

Beech, Martin. *The Pillars of Creation: Giant Molecular Clouds, Star Formation, and Cosmic Recycling.* Cham, Switzerland: Springer Praxis Books, 2017. A well-written introduction to the process of star formation.

Bland-Hawthorn, Joss, and Ortwin Gerhard. "The Galaxy in Context: Structural, Kinematic, and Integrated Properties." *Annual Review of Astronomy and Astrophysics* 54 (2016): 529–596. A detailed research review of the observational and theoretical studies of the overall structure of the Milky Way Galaxy.

Bok, Bart J., and Priscilla F. Bok. *The Milky Way.* 5th ed. Cambridge, MA: Harvard University Press, 1981. The classic introductory text on the Milky Way Galaxy.

Branch, David, and J. Craig Wheeler. *Supernova Explosions.* Berlin, Germany: Springer-Verlag, 2017. A detailed and thorough introduction to the astrophysics of supernovas and their remnants.

Chambers, John, and Jacqueline Mitton. *From Dust to Life: The Origin and Evolution of Our Solar System.* Princeton, NJ: Princeton University Press, 2013. An excellent introduction to the formation and evolution of the solar system.

Christensen, Lars Lindberg, Davide De Martin, and Raquel Yumi Shida. *Cosmic Collisions: The Hubble Atlas of Merging Galaxies*. New York: Springer, 2009. A well-illustrated atlas and overview of the colliding galaxies observed with the Hubble Space Telescope.

Christianson, Gale E. *Edwin Hubble: Mariner of the Nebulae*. New York: Farrar, Straus, and Giroux, 1995. A detailed biography of the life and science of Edwin Hubble.

D'Onghia, Elena, and Andrew J. Fox. "The Magellanic Stream: Circumnavigating the Galaxy." *Annual Review of Astronomy and Astrophysics* 54 (2016): 363–400. A detailed research review of the observational and theoretical studies of the Magellanic Stream.

Devorkin, David, and Robert W. Smith. *The Hubble Cosmos: 25 Years of New Vistas in Space*. Washington, DC: National Geographic, 2015. A beautiful compilation and discussion of the most spectacular images taken by the Hubble Space Telescope.

Dickinson, Terence. *Hubble's Universe: Greatest Discoveries and Latest Images.* 2nd ed. Buffalo, NY: Firefly Books, 2017. A beautiful compilation and discussion of the most spectacular images taken by the Hubble Space Telescope.

Eicher, David J. *Comets! Visitors from Deep Space.* New York: Cambridge University Press, 2013. An excellent introduction to the astrophysics of comets and the history of their observation on the sky.

Fletcher, Seth. *Einstein's Shadow: A Black Hole, a Band of Astronomers, and the Quest to See the Unseeable.* New York: HarperCollins Publishers, 2018. The inside story about the development of the Event Horizon Telescope and the search for the shadow of the supermassive black hole at the galactic center.

Frebel, Anna. *Searching for the Oldest Stars: Ancient Relics from the Early Universe.* Princeton, NJ: Princeton University Press, 2015. An excellent introduction to stars, stellar evolution, and stellar nucleosynthesis, with a particular focus on the oldest stars in the Milky Way.

Frisch, Priscilla C. "The Galactic Environment of the Sun." *American Scientist* 88 (January–February 2000): 52–59. A well-illustrated, popular article about the Local Bubble and other details regarding the interstellar environment surrounding the Sun.

Greene, Jenny E. “Goldilocks Black Holes.” *Scientific American* 306 (January 2012): 40–47. An informative, popular article about forming the seeds of supermassive black holes at the center of the Milky Way and other galaxies.

Hartquist, T. W., J. E. Dyson, and D. P. Ruffle. *Blowing Bubbles in the Cosmos: Astronomical Winds, Jets, and Explosions*. New York: Oxford University Press, 2004. A detailed introduction to the astrophysics of mass loss from stars.

Hubble, Edwin. *The Realm of the Nebulae.* repr. ed. New Haven, CT: Yale University Press, 2013. This is a reprint edition of Hubble’s classic 1936 treatise on the extragalactic universe, with forewords from some of today’s researchers, giving it a modern perspective.

Kirshner, Robert P. “The Supernova of a Lifetime.” *Sky and Telescope* 133 (February 2017): 36–40. A well-illustrated, popular article about Supernova 1987A in the Large Magellanic Cloud on its 30th anniversary.

Kwok, Sun. *Stardust: The Cosmic Seeds of Life.* Berlin, Germany: Springer-Verlag, 2013. A well-written introduction to the recycling of stardust and complex molecules between stars and the interstellar medium.

Launius, Roger D., and David H. Devorkin, eds. *Hubble’s Legacy: Reflections by Those Who Dreamed It, Built It, and Observed the Universe with It.* Washington, DC: Smithsonian Institution Scholarly Press, 2014. Detailed insights into all aspects of the Hubble Space Telescope mission by a group of scientists and other experts.

Pasachoff, Jay M., and Alex Filippenko. *The Cosmos: Astronomy in the New Millenium*. 5th ed. Cambridge, UK: Cambridge University Press, 2019. A thorough, well-illustrated introductory textbook on astronomy.

Percy, John R. *Understanding Variable Stars.* Cambridge, UK: Cambridge University Press, 2007. An excellent and thorough introduction to variable stars.

Portegies Zwart, Simon F. “The Long-Lost Siblings of the Sun.” *Scientific American* 301 (November 2009): 40–47. An informative, well-illustrated, popular article about the Sun’s formation and original evolution in a star cluster.

Portegies Zwart, Simon F., Stephen L. W. McMillan, and Mark Gieles. "Young Massive Star Clusters." *Annual Review of Astronomy and Astrophysics* 48 (2010): 431–493. A detailed research review of the observational and theoretical studies of young massive star clusters.

Rector, Travis, Kimberly Arcand, and Megan Watzke. *Coloring the Universe: An Insider's Look at Making Spectacular Images of Space.* Fairbanks, AK: University of Alaska Press, 2015. A well-illustrated introduction to astronomical imaging.

Schilling, Govert, and Wil Tirion. *Constellations: The Story of Space Told through the 88 Known Star Patterns in the Night Sky.* New York: Black Dog & Leventhal Publishers, 2019. A well-illustrated introduction to the night sky's constellations.

Seargent, David. *The Greatest Comets in History: Broom Stars and Celestial Scimitars.* New York: Springer Science+Business Media, 2009. A thorough discussion of the greatest comets observed on the sky throughout history.

Sheehan, William, and Christopher J. Conselice. *Galactic Encounters: Our Majestic and Evolving Star-System, From the Big Bang to Time's End.* New York: Springer, 2016. A well-written, well-illustrated introduction to the study of the Milky Way and other galaxies from a historical perspective.

Sobel, Dava. *The Glass Universe: How the Ladies of the Harvard Observatory Took the Measure of the Stars.* New York: Viking, 2016. An excellent historical introduction to the female astronomers at Harvard who made the fundamental stellar measurements that underlie much of modern astrophysics today.

Stevenson, David. *The Complex Lives of Star Clusters.* Cham, Switzerland: Springer International Publishing, 2015. A clear introduction to the astrophysics of open and globular star clusters.

Struck, Curtis. *Galaxy Collisions: Forging New Worlds from Cosmic Crashes.* New York: Springer, 2011. A well-written introduction to the astrophysics of interacting galaxies.

Van Den Bergh, Sidney. *The Galaxies of the Local Group*. Cambridge, UK: Cambridge University Press, 2000. A thorough introduction to the galaxies of the Local Group.

Waller, William H. *The Milky Way: An Insider's Guide.* Princeton, NJ: Princeton University Press, 2013. An excellent introduction to the structure and evolution of the stars and interstellar clouds making up the Milky Way Galaxy.

Weintraub, David. *How Old Is the Universe?* Princeton, NJ: Princeton University Press, 2011. An excellent introduction to how the ages of the solar system, star clusters, and universe are determined.

Young, Monica. "Spirits of Our Galaxy's Past." *Sky and Telescope* 133 (April 2017): 22–29. A well-illustrated, popular article about the star streams observed in the galactic halo.

Zimmerman, Robert. "Spider Webs in Space." *Sky and Telescope* 128 (November 2014): 20–26. A well-illustrated, popular article about the wide variety of structures observed in planetary nebulae.

———. *The Universe in a Mirror: The Saga of the Hubble Space Telescope and the Visionaries Who Built It.* Princeton, NJ: Princeton University Press, 2008. An excellent behind-the-scenes history of the Hubble Space Telescope, from its original idea through its many discoveries in orbit.

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