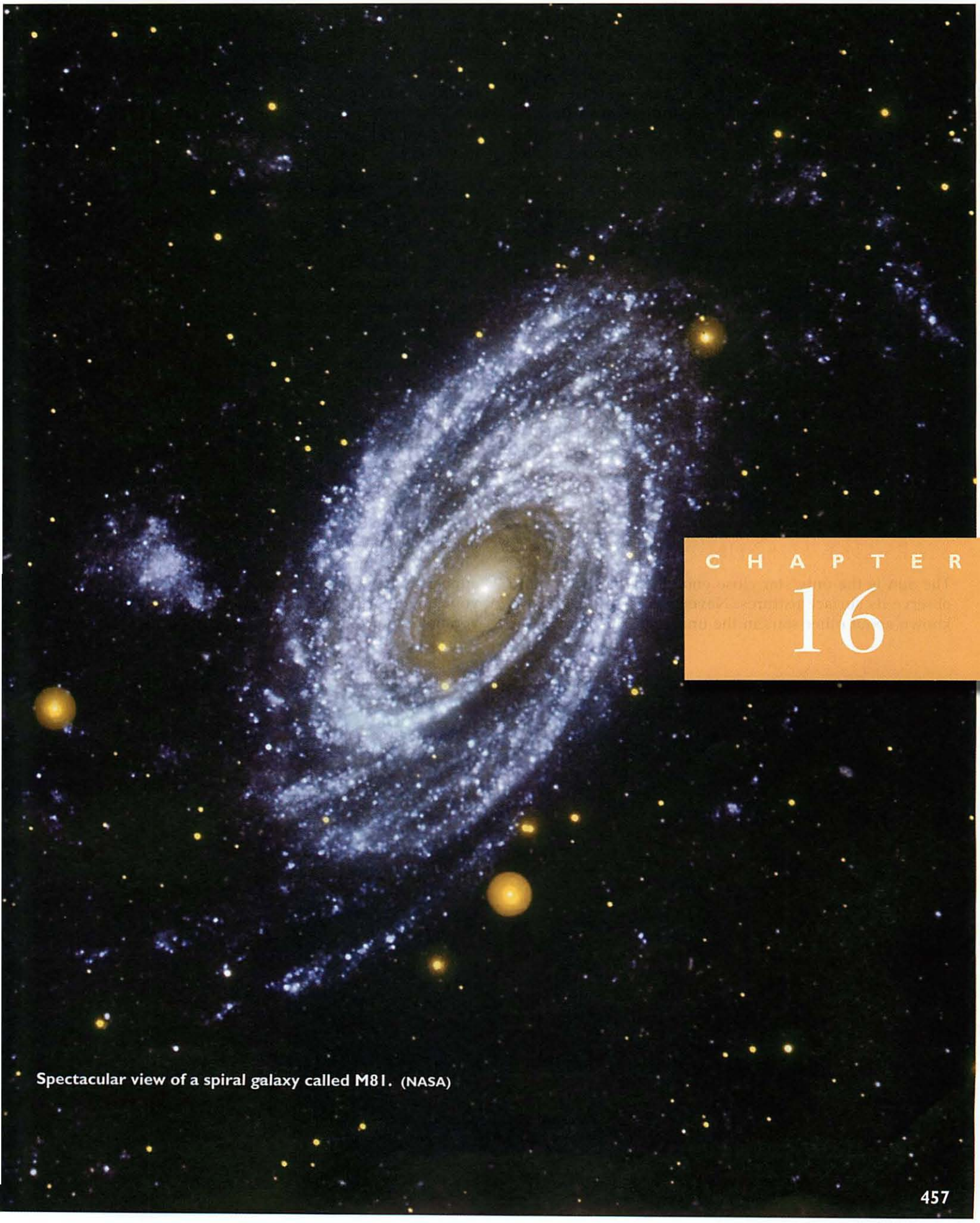
BEYOND OUR SOLAR SYSTEM*

FOCUS ON LEARNING

To assist you in learning the important concepts in this chapter, you will find it helpful to focus on the following questions:

1. How is the principle of parallax used to measure the distance to a star?
2. What are the major intrinsic properties of stars?
3. What are the size categories of stars?
4. What are the different types of nebulae?
5. What is the most plausible model for stellar evolution? What are the stages in the life cycle of a star?
6. What are the possible final states that a star may assume after it consumes its nuclear fuel and collapses?
7. What is our own Milky Way Galaxy like?
8. What are the different types of galaxies?
9. What is the Doppler shift?
10. What is the big bang theory for the origin of the universe?

*This chapter was revised with the assistance of Teresa Tarbuck and Mark Watry.



CHAPTER

16

Spectacular view of a spiral galaxy called M81. (NASA)

Aside from the Sun, Moon, several planets, and the occasional comet or meteor, every celestial object we see with our naked eye lies beyond our solar system. The closest star to Earth, other than the Sun, is Proxima Centauri, which is about 4.3 light-years away—roughly 100 million times farther than the Moon. To appreciate how far this is, imagine that the Earth and Moon are dots on a sheet of paper one millimeter apart. On this scale, the Sun is 390 millimeters (about 15 inches) away, and Proxima Centauri is about 100,000 kilometers (62,000 miles) away! That is one long sheet of paper! It would wrap around Earth two and one-half times. Also on this scale, the *nearest galaxy* lies 60 billion kilometers away. These facts suggest that the universe is incomprehensibly large. It is also incomprehensibly empty, containing on average about one hydrogen atom per cubic centimeter.

Astronomers and cosmologists* study the nature of this vast cosmos, trying to answer questions such as: Is our Sun a typical star? Do other stars have solar systems with planets like Earth? How large is the universe? Did it have a beginning? Will it have an end? This chapter explores the answers to these questions.

*Cosmologists study the origin and evolution of the universe.

STARS LIKE THE SUN

The Sun is the only star close enough to Earth for us to observe its surface features. Nevertheless, a great deal is known about other stars in the universe. This knowledge relies on the fact that stars and hot clouds of gas radiate tremendous amounts of energy in all directions into space (**FIGURE 16.1**). The key to understanding the universe is to collect this radiation and unravel the clues it holds. Astronomers have devised many ingenious methods to do just that.

Measuring Distances to the Closest Stars

Measuring the distance to a star is difficult. Obviously, we cannot journey to the star, and even if we had an extremely powerful laser range finder, it would take over eight years to receive the return signal from the nearest star. Even then, we would have to be in the right place to catch the return signal. Nevertheless, astronomers have developed some indirect methods to measure stellar distances. The most basic of these measurements is called *stellar parallax*, a measurement that is limited to determining the distances to only the closest stars.

Recall from Chapter 15 that **stellar parallax** is the very slight back-and-forth shift of the apparent position of a nearby star due to the orbital motion of Earth around the Sun. The principle of parallax is easy to visualize. Close one eye, and with your index finger in a vertical position, use your open eye to line up your finger with some distant object. Without moving your finger or your head, view the object with your other eye and notice that its position appears to have changed. Now repeat the exercise holding your finger farther away, and notice that the farther away you hold your finger, the less its position seems to shift.

FIGURE 16.1 Lagoon Nebula. It is in glowing clouds like these that gases and dust particles become concentrated into stars. (Courtesy of National Optical Astronomy Observatories)

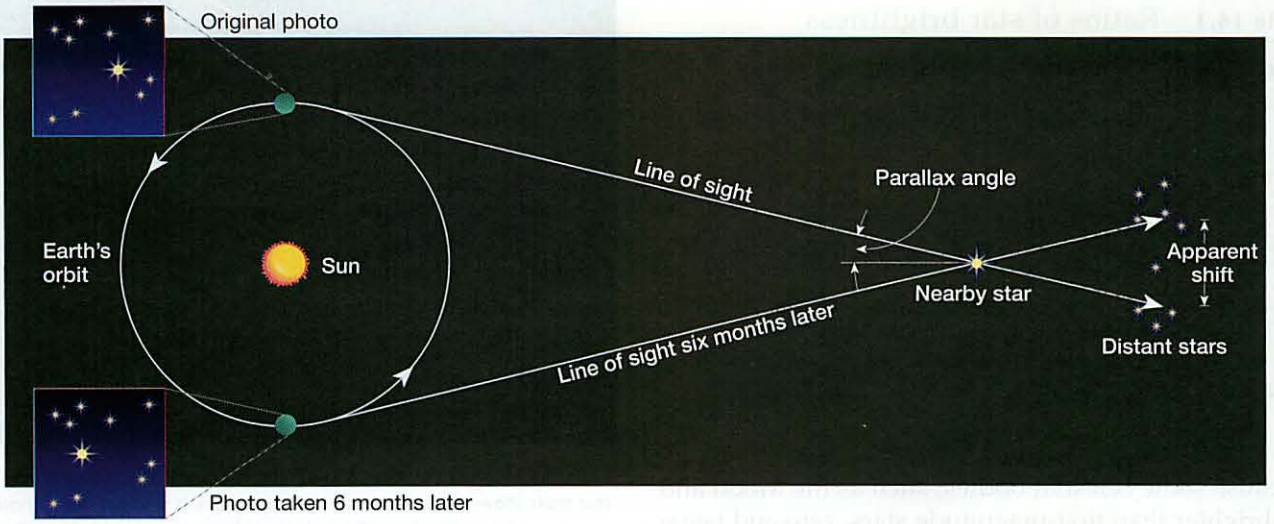


FIGURE 16.2 Geometry of stellar parallax. The parallax angle shown here is enormously exaggerated to illustrate the principle. Because distances to even the nearest stars are thousands of times greater than the Earth–Sun distance, the triangles that astronomers work with are extremely long and narrow, making the angles that are measured very small.

In principle, this method of measuring stellar distances is elementary and was known to the ancient Greeks. Today, parallax is determined by photographing a nearby star against the background of distant stars. Then, six months later, when Earth has moved halfway around its orbit, a second photograph is taken. When these photographs are compared, the position of the nearby star appears to have shifted with respect to the background stars. **FIGURE 16.2** illustrates this shift and the parallax angle determined from it. The nearest stars have the largest parallax angles, whereas those of distant stars are much too small to measure. Recall that the sixteenth-century astronomer Tycho Brahe was unable to detect stellar parallax for any stars, leading him to reject the idea that Earth orbits the Sun.

In practice, parallax measurements are greatly complicated because of the tiny angles involved and because the Sun and the star being measured are moving in different directions. The first accurate stellar parallax was not determined until 1838. Even today, parallax angles for only a few thousand of the nearest stars are known with certainty. Almost all the other stars have such small parallax shifts that accurate measurements are not possible. Fortunately, other methods have been developed to estimate distances to more distant stars. In addition, the Hubble Space Telescope, which is not hindered by Earth's light-distorting atmosphere, has obtained accurate parallax distances for many more stars.

Minute parallax angles prove that the distances to stars are enormous, so large that conventional units of length, such as kilometers or astronomical units, are too cumbersome to use. A better unit to express stellar distances is the **light-year**, which is the distance light travels in one Earth-year—about 9.5 trillion kilometers (5.8 trillion miles).

Stellar Brightness

The oldest means of classifying stars is based on their *brightness*, also called *luminosity* or *magnitude*. It is natural to assume that very bright stars are somehow different from very dim stars. Three factors control the brightness of a star as seen from Earth: *how big* it is, *how hot* it is, and *how far away* it is. The stars in the night sky come in a grand assortment of sizes, temperatures, and distances, so their apparent brightnesses vary widely.

Apparent Magnitude

Stars have been classified according to their apparent brightness since at least the second century B.C., when Hipparchus placed about 850 of them into six categories based on his ability to see differences in brightness. Because he could only reliably see six different brightness levels, he created six categories. These categories were later called **magnitudes**, with *first magnitude (low numerical value) being the brightest and sixth magnitude (high numerical value) the dimmest*. Since some stars may appear dimmer than others only because they are farther away, a star's brightness, *as it appears when viewed from Earth*, is called its **apparent magnitude**. With the invention of the telescope, many stars fainter than the sixth magnitude were discovered.

In the mid-1800s, a method was developed to standardize the magnitude scale. An absolute comparison was made between the light coming from stars of the first magnitude and stars of the sixth magnitude. It was determined that a first-magnitude star was about 100 times brighter than a sixth-magnitude star. On the scale that was devised, any two stars that differ by 5 magnitudes have a ratio in brightness of 100 to 1. Hence, a third-magnitude star is 100 times brighter than an eighth-magnitude star. It follows, then, that the brightness ratio of two stars differing by only one magnitude is about 2.5.* A star of the first magnitude is about 2.5 times brighter than a star of the second magnitude. Table 16.1 shows how differences in magnitude correspond to brightness ratios.

*Calculations: or $2.512 \times 2.512 \times 2.512 \times 2.512 \times 2.512$, or 2.512 raised to the fifth power, equals 100.

Table 16.1 Ratios of star brightness

Difference in Magnitude	Brightness Ratio
0.5	1.6:1
1	2.5:1
2	6.3:1
3	16:1
4	40:1
5	100:1
10	10,000:1
20	100,000,000:1

Because some celestial bodies, such as the Moon and Sun, are brighter than first-magnitude stars, zero and negative magnitudes were introduced. On this scale, the Sun has an apparent magnitude of −26.7. At its brightest, Venus has a magnitude of −4.3. At the other end of the scale, the 5-meter (200-inch) Hale Telescope can view stars with an apparent magnitude of 23, approximately 100 million times dimmer than stars that are visible to the unaided eye, and the Hubble Space Telescope can "see" stars with an apparent magnitude of 30!

Absolute Magnitude

Apparent magnitudes were good approximations of the true brightness of stars when astronomers thought that the universe was very small—containing no more than a few thousand stars that were all at very similar distances from Earth. However, we now know that the universe is unimaginably large and contains innumerable stars at wildly varying distances. Since astronomers are interested in the "true" brightness of stars, they devised a measure called **absolute magnitude**.

Stars of the same apparent magnitude usually do not have the same brightness because their distances from us are not equal. Imagine that you see a plane flying overhead at night. Although the lights on the plane may look brighter than the stars behind them, we know they are not as luminous.

Table 16.2 Distance, apparent magnitude, and absolute magnitude of some stars

Name	Distance (light-years)	Apparent Magnitude*	Absolute Magnitude*
Sun	NA	−26.7	5.0
Alpha Centauri	4.27	0.0	4.4
Sirius	8.70	−1.4	1.5
Arcturus	36	−0.1	−0.3
Betelgeuse	520	0.8	−5.5
Deneb	1600	1.3	−6.9

*The more negative (smaller) the number, the brighter; the more positive (larger) the number, the dimmer.

FIGURE 16.3 Time-lapse photograph of stars in the constellation Orion. These star trails show some of the various star colors. It is important to note that the eye sees color somewhat differently than does photographic film. (Courtesy of National Optical Astronomy Observatories)

Astronomers correct for distance by determining what brightness (magnitude) the stars would have if they were at a standard distance—about 32.6 light-years away from Earth. For example, the Sun, which has an apparent magnitude of −26.7, would, if located at a distance of 32.6 light-years, have an absolute magnitude of about +5. Thus, stars with absolute magnitudes greater than +5 (smaller numerical value) are intrinsically brighter than the Sun. It is only because of their distance that they appear much dimmer. Table 16.2 lists the absolute and apparent magnitudes of some stars as well as their distances from Earth. Most stars have an absolute magnitude between −5 (very bright) and +15 (very dim). The Sun is near the middle of this range.

Stellar Color and Temperature

The next time you are outdoors on a clear night, take a good look at the stars and note their color (**FIGURE 16.3**). Because our eyes do not respond to color very well in low-intensity light, look at the brightest stars. Some that are quite colorful can be found in the constellation Orion. Of the two brightest stars in Orion, Rigel (β Orionis) appears blue, whereas Betelgeuse (α Orionis) is definitely red.

Very hot stars with surface temperatures above 30,000 K (kelvin) emit most of their energy in the form of short-wavelength light and therefore appear blue. On the other hand, cooler red stars, with surface temperatures generally less than 3000 K, emit most of their energy as longer-wavelength red light. Stars, such as the Sun, with surface temperatures between 5000 and 6000 K, appear yellow. Because color is primarily a manifestation of a star's surface temperature, this characteristic provides astronomers with useful information about a star. As you will see, combining temperature data with stellar magnitude tells us a great deal about the size and mass of a star.

Binary Stars and Stellar Mass

One of the night sky's best-known constellations, the Big Dipper, appears to consist of seven stars. But those with good eyesight can recognize that the second star in the handle is actually two stars. During the eighteenth century, astronomers used their new tool, the telescope, to discover numerous such star pairs. One of the stars in the pair was usually fainter than the other, and for this reason it was considered to be farther away. In other words, the stars were not considered true pairs but were thought only to lie along the same line of sight.

In the early nineteenth century, careful examination of numerous star pairs by William Herschel showed that many stars found in pairs actually orbit one another. The two stars are in fact united by their mutual gravitation. These pairs of stars, in which the members are far enough apart to be resolved telescopically, are called **visual binaries** (*binaries* = double). The idea of one star orbiting another may seem unusual, but more than half of the stars in the universe exist in pairs or multiples.

Binary stars can be used to determine the star property most difficult to calculate—its *mass*. The mass of a body can be established if it is gravitationally attached to a partner. Binary stars orbit each other around a common point called the *center of mass* (**FIGURE 16.4**). For stars of equal mass, the center of mass lies exactly halfway between them. When one star is more massive than its partner, their common center will be located closer to the more massive one. Thus, if the sizes of their orbits can be observed, a determination of their individual masses can be made. You can experience this relationship on a seesaw by trying to balance a person who has a much greater (or smaller) mass.

For illustration, when one star has an orbit half the size (radius) of its companion, it is twice as massive as its companion. If their combined masses are equal to three solar masses, then the larger will be twice as massive as the Sun, and the smaller will have a mass equal to that of the Sun. Most stars have a mass that falls in a range between 1/10 and 50 times the mass of the Sun.

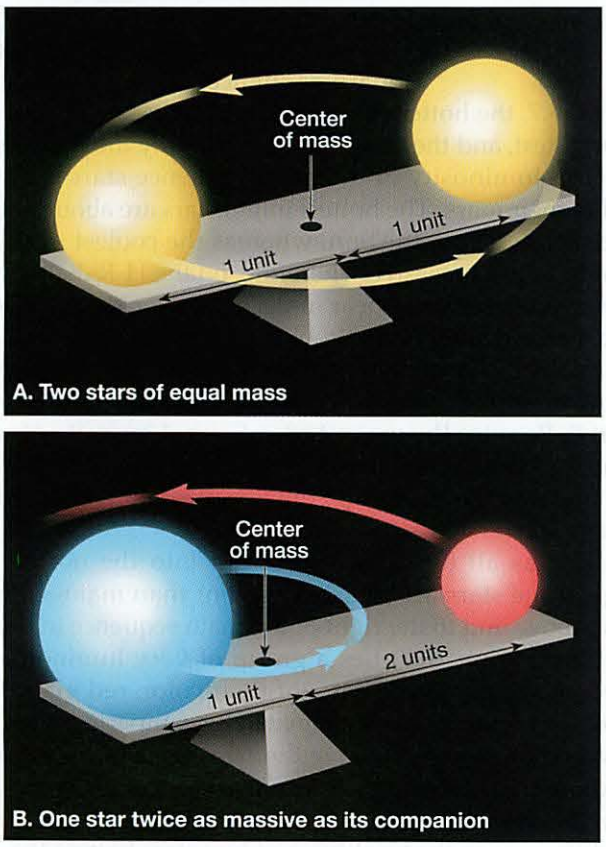


FIGURE 16.4 Binary stars orbit each other around their common center of mass. **A.** For stars of equal mass, the center of mass lies exactly halfway between them. **B.** If one star is twice as massive as its companion, it is twice as close to their common center of mass. Therefore, more massive stars have proportionately smaller orbits than do their less massive companions.

VARIABLE STARS

Not all stars release a relatively steady stream of energy like our Sun. Stars that fluctuate in brightness are known as variable stars. Some, called **pulsating variables**, fluctuate regularly in brightness by expanding and contracting in size. Astronomers study variable stars for many reasons, including trying to determine whether average stars such as the Sun spend some of their lives as variable stars, and if so, what kind.

The most spectacular variable stars belong to a group known as **eruptive variables**. When one of these explosive events occurs, it appears as a sudden brightening of a star, called a **nova** (**FIGURE 16.5**). The term *nova*, meaning "new," was used by the ancients because these stars were unknown to them before their abrupt increase in luminosity.

During a nova event, the outer shell of the star is ejected outward at high speed. A nova generally reaches maximum brightness in a couple of days, remains bright for only a few weeks, then slowly returns in a year or so to its original brightness. Because the star returns to its prenova brightness, we can assume that only a small amount of its mass is lost during the flare-up. Some stars have experienced more than one such event. In fact, the process probably occurs repeatedly.

The modern explanation for novae proposes that they occur in binary systems consisting of an expanding *red giant* and a hot *white dwarf*. Hydrogen-rich gas from the oversized giant encroaches near enough to the white dwarf to be gravitationally transferred. Eventually, enough hydrogen-rich gas is transferred to the hot dwarf to cause it to explosively ignite. Such a thermonuclear reaction rapidly heats and expands the outer gaseous envelope of the white dwarf to produce a nova event. In a relatively short time, the white dwarf returns to its prenova state, where it remains inactive until the next buildup occurs.

Like a nova, a **supernova** is a star that dramatically increases in brightness. However, the two phenomena are different. A supernova is a catastrophic event radiating as much energy in a few months as the Sun will radiate in its entire lifetime. In addition, during a supernova event the star's outer shell is explosively ejected, a topic we will consider later (**FIGURE 16.6**).

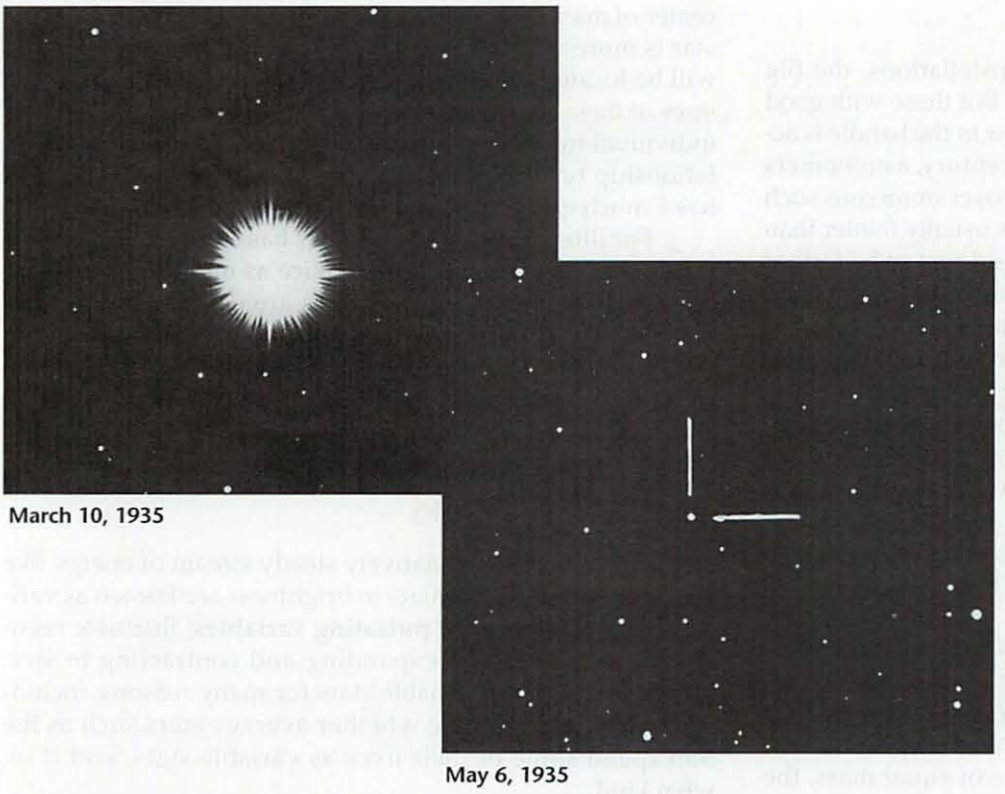


FIGURE 16.5 Photographs of Nova Herculis (a nova in the constellation Hercules), taken about two months apart, showing the decrease in brightness. (Courtesy of Lick Observatory)

FIGURE 16.6 This false-color image from three of NASA's Great Observatories provides one example of a star that died in a fiery supernova blast. Called Cassiopeia A, this supernova remnant is located 10,000 light-years away in the constellation Cassiopeia. At the center, visible only as a tiny turquoise dot, is the leftover corpse of the now-dead star, called a neutron star. (NASA)

HERTZSPRUNG-RUSSELL DIAGRAM

Early in the twentieth century, Einar Hertzsprung and Henry Russell independently studied the relationship between the true brightness (absolute magnitude) of stars and their temperatures. From this research each developed a graph, now called a **Hertzsprung-Russell diagram (H-R diagram)**, that displays these intrinsic stellar properties. By studying H-R diagrams, we can learn a great deal about the relationships among the sizes, colors, and temperatures of stars.

To produce an H-R diagram, astronomers survey a portion of the sky and plot each star according to its luminosity (brightness) and temperature (**FIGURE 16.7**). Notice that the stars in Figure 16.7 are not uniformly distributed. Rather, about 90 percent of all stars fall along a band that runs from the upper-left corner to the lower-right corner of the H-R diagram. These "ordinary" stars are called **main-sequence stars**. As shown in Figure 16.7, the hottest main-sequence stars are intrinsically the brightest, and the coolest are intrinsically the dimmest.

The luminosity of the main-sequence stars is also related to their mass. The hottest (blue) stars are about 50 times more massive than the Sun, whereas the coolest (red) stars are only 1/10 as massive. Therefore, on the H-R diagram, the main-sequence stars appear in decreasing order, from hotter, more massive blue stars to cooler, less massive red stars.

Note the location of the Sun in Figure 16.7. The Sun is a yellow main-sequence star with an absolute magnitude of about 5. Because the magnitude of a vast majority of main-sequence stars lie between −5 and 15, and because the Sun falls midway in this range, the Sun is often considered an average star.

Just as all humans do not fall into the normal size range, some stars are clearly different than main-sequence stars. Above and to the right of the main sequence in the H-R diagram (Figure 16.7) lies a group of very luminous stars called *giants*, or, on the basis of their color, **red giants**. The size of these giants can be estimated by comparing them with stars of known size that have the same surface temperature. We know that objects having equal surface temperatures radiate the same amount of energy per unit area. Therefore, any difference in the brightness of two stars having the same surface temperature is attributable to their relative sizes.

For example, a red main-sequence star and another red star that is 100 times more luminous radiate the same amount of energy per unit area. Therefore, in order for the

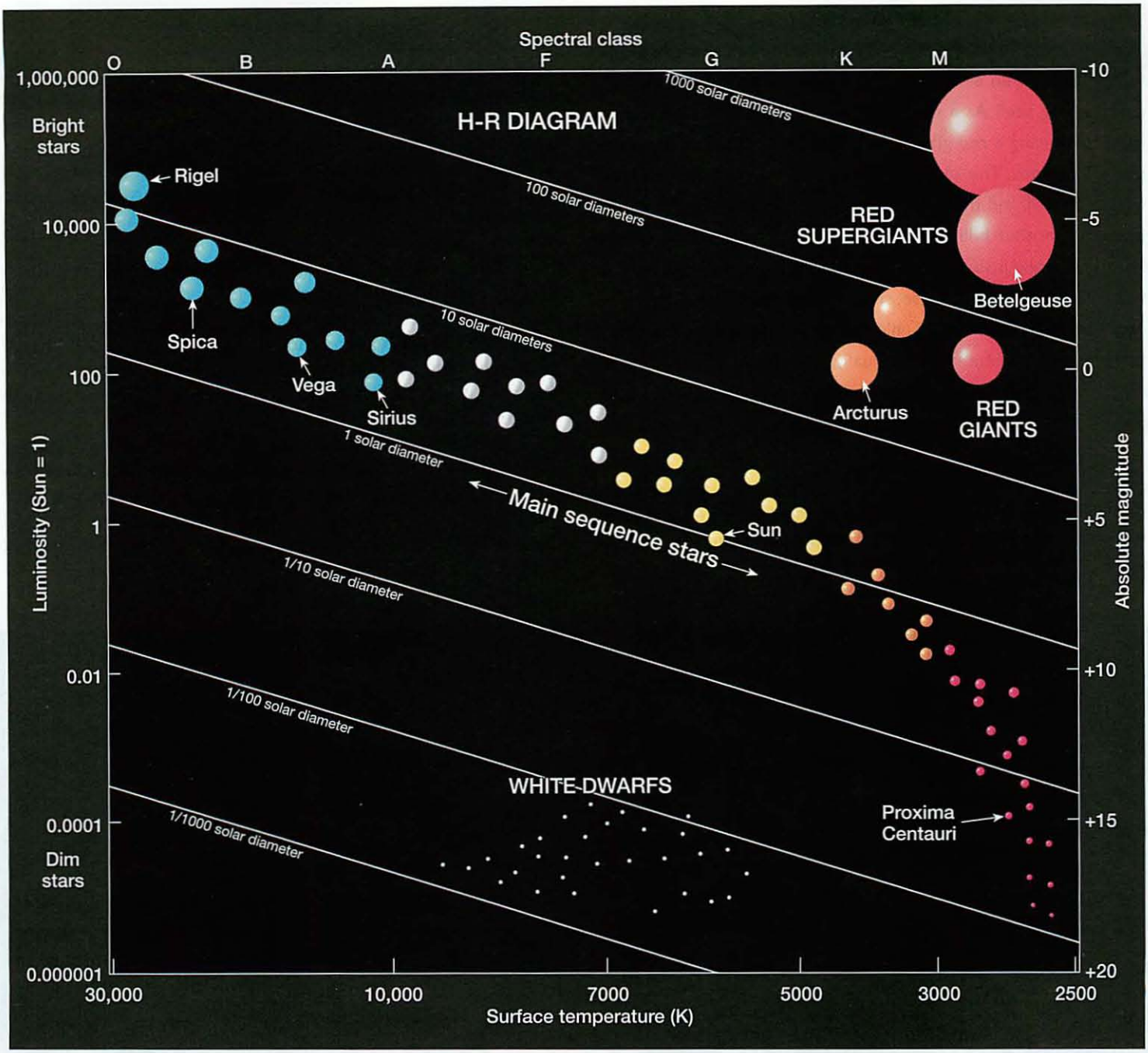


FIGURE 16.7 Idealized Hertzsprung-Russell diagram on which stars are plotted according to temperature and absolute magnitude.

more luminous star to be 100 times brighter than the less luminous star, it must have 100 times more surface area. Stars with large radiating surfaces appear in the upper-right position of an H-R diagram and are appropriately called *giants*.

Some stars are so large that they are called **supergiants**. Betelgeuse, a bright red supergiant in the constellation Orion, has a radius about 800 times that of the Sun. If this star were at the center of our solar system, it would extend beyond the orbit of Mars, and Earth would find itself inside the star! Other red giants that are easy to locate are Arcturus in the constellation Bootes and Antares in Scorpius.

In the lower-left portion of the H-R diagram, the opposite situation arises. These stars are much fainter than main-sequence stars of the same temperature, and by using the same reasoning, they must be much smaller. Some probably approximate Earth in size. This group has come to be called **white dwarfs**.

Soon after the first H-R diagrams were developed, astronomers realized their importance in interpreting stellar evolution. Just as with living things, a star is born, ages, and dies. Owing to the fact that almost 90 percent of the stars lie on the main sequence, we can be relatively certain that stars spend most of their active years as main-sequence stars.

DID YOU KNOW?

In a few billion years, the Sun will exhaust the remaining hydrogen fuel in its core, an event that will trigger hydrogen fusion in the surrounding shell. As a result, the Sun's outer envelope will expand, producing a red giant that is hundreds of times larger and more luminous. The intense solar radiation will cause Earth's oceans to boil, and the solar winds will drive away Earth's atmosphere. In another billion years, the Sun will expel its outermost layer, producing a spectacular planetary nebula, while its interior will collapse to form a dense, small (planet-size), white dwarf. Because of its small size, the Sun's energy output will be less than 1 percent of its current level. Gradually, the Sun will emit its remaining thermal energy, eventually becoming a cold, nonluminous body.

Only a few percent are giants, and perhaps 10 percent are white dwarfs. After a brief discussion of interstellar matter, we will come back to stellar evolution and the life cycle of stars.

INTERSTELLAR MATTER

Lying between the stars is "the vacuum of space." However, it is far from a perfect vacuum, for it is populated with accumulations of dust and gases. The name applied to these concentrations of interstellar matter is **nebula** (*nebula* = cloud). If this interstellar matter is close to very hot (blue) stars, it will glow and is called a **bright nebula** (**FIGURE 16.8**). The two main types of bright nebulae are known as *emission nebulae* and *reflection nebulae*.

Emission nebulae are gaseous masses that consist largely of hydrogen. They absorb *ultraviolet radiation* emitted by embedded or nearby hot stars. Because these gases are under very low pressure, they reradiate, or emit, this energy as *visible light*. This conversion of ultraviolet light to visible light is known as *fluorescence*, an effect you observe daily in fluorescent lights.

Reflection nebulae, as the name implies, merely reflect the light of nearby stars (**FIGURE 16.9**). Reflection nebulae are likely composed of relatively dense clouds of large particles called **interstellar dust**. This view is supported by the fact that atomic gases with low densities could not reflect light sufficiently to produce the glow observed.

FIGURE 16.8 The Trifid Nebula, in the constellation Sagittarius. This colorful nebula is a cloud consisting mostly of hydrogen and helium gases. These gases are excited by the radiation of the hot, young stars within and produce a reddish glow. (Courtesy of National Optical Astronomy Observatories)

FIGURE 16.9 A faint blue reflection nebula, in the Pleiades star cluster, is caused by the reflection of starlight from dust in the nebula. The Pleiades star cluster, just visible to the naked eye in the constellation Taurus, is spectacular when viewed through binoculars or a small telescope. (Palomar Observatories/California Institute of Technology [Caltech])

When a cloud of interstellar material is not close enough to a bright star to be illuminated, it is referred to as a **dark nebula**. Exemplified by the Horsehead Nebula in Orion, dark nebulae appear as opaque objects silhouetted against a bright background (**FIGURE 16.10**). Dark nebulae can also easily be seen as starless regions—"holes in the heavens" when viewing the Milky Way.

Although nebulae appear very dense, they actually consist of very thinly scattered matter. Because of their enormous size, however, the total mass of rarefied particles and molecules are many times that of the Sun. Interstellar matter is of great interest to astronomers because it is from this material that stars and planets are formed.

STELLAR EVOLUTION

The idea of describing how a star is born, ages, and then dies may seem a bit presumptuous, for many of these objects have life spans that exceed billions of years. However, by studying stars of different ages, at different points in their life cycles, astronomers have been able to piece together a plausible model for stellar evolution.

The method that was used to create this model is analogous to what an alien being, upon reaching Earth, might use to determine the developmental stages of human life. By examining a large number of humans, this stranger would be able to observe the birth of human life, the activities of children and adults, and the death of the elderly. From this information, the alien could put the stages of human development into their proper sequence. Based on the relative abundance of humans in each stage of development, it would even be possible to conclude that humans spend more of their lives as adults than as toddlers. In a similar fashion, astronomers have pieced together the life story of stars.

In the simplest sense, every stage of a star's life is ruled by gravity. The mutual gravitational attraction of particles in a thin, gaseous cloud causes the cloud to collapse. As the cloud is squeezed to unimaginable pressures, its temperature rises, igniting its nuclear furnace, and a star is born. A star is a ball of very hot gases, caught between the opposing forces of gravity trying to contract it and thermal nuclear energy trying to expand it. Eventually, all of a star's nuclear fuel will be exhausted and gravity takes control, collapsing the stellar remnant into a comparatively small, dense body.

Stellar Birth

The birthplaces of stars are dark, cool interstellar clouds, which are rich in dust and gases (**FIGURE 16.11**). In the Milky Way, these gaseous clouds consist of 92 percent hydrogen, 7 percent helium, and less than 1 percent of the remaining heavier elements. One mechanism thought to trigger stellar formation is a shock wave generated by a catastrophic explosion (supernova) of a nearby star. Regardless of the force that initiates the process, once it is started, mutual gravitational attraction of the particles causes the cloud to contract, pulling every particle toward the center. As the cloud shrinks, gravitational energy (potential energy) is converted into energy of motion, or heat energy, and the contracting gases slowly heat up.

The initial contraction spans a million years. With the passage of time, the temperature of this gaseous body slowly and continuously rises, eventually reaching a temperature sufficiently high to cause it to radiate energy from its surface in the form of long-wavelength red light. Because this large red object is not hot enough to engage in nuclear fusion, it is not yet a star. The name **protostar** is applied to these bodies.

Protostar Stage

During the protostar stage, gravitational contraction continues, slowly at first, then much more rapidly (Figure 16.11). This collapse causes the core of the developing star to heat much more intensely than the outer envelope. When the core reaches a temperature of 10 million K, the pressure within is so great that groups of four hydrogen nuclei fuse together into single helium nuclei. Astronomers refer to this nuclear reaction as **hydrogen burning** because an enormous amount of energy is released. However, keep in mind that thermonuclear "burning" is not burning in the usual chemical sense of a wood or coal fire.

Immense heat released by hydrogen fusion causes the gases inside the star to move with increased vigor, resulting

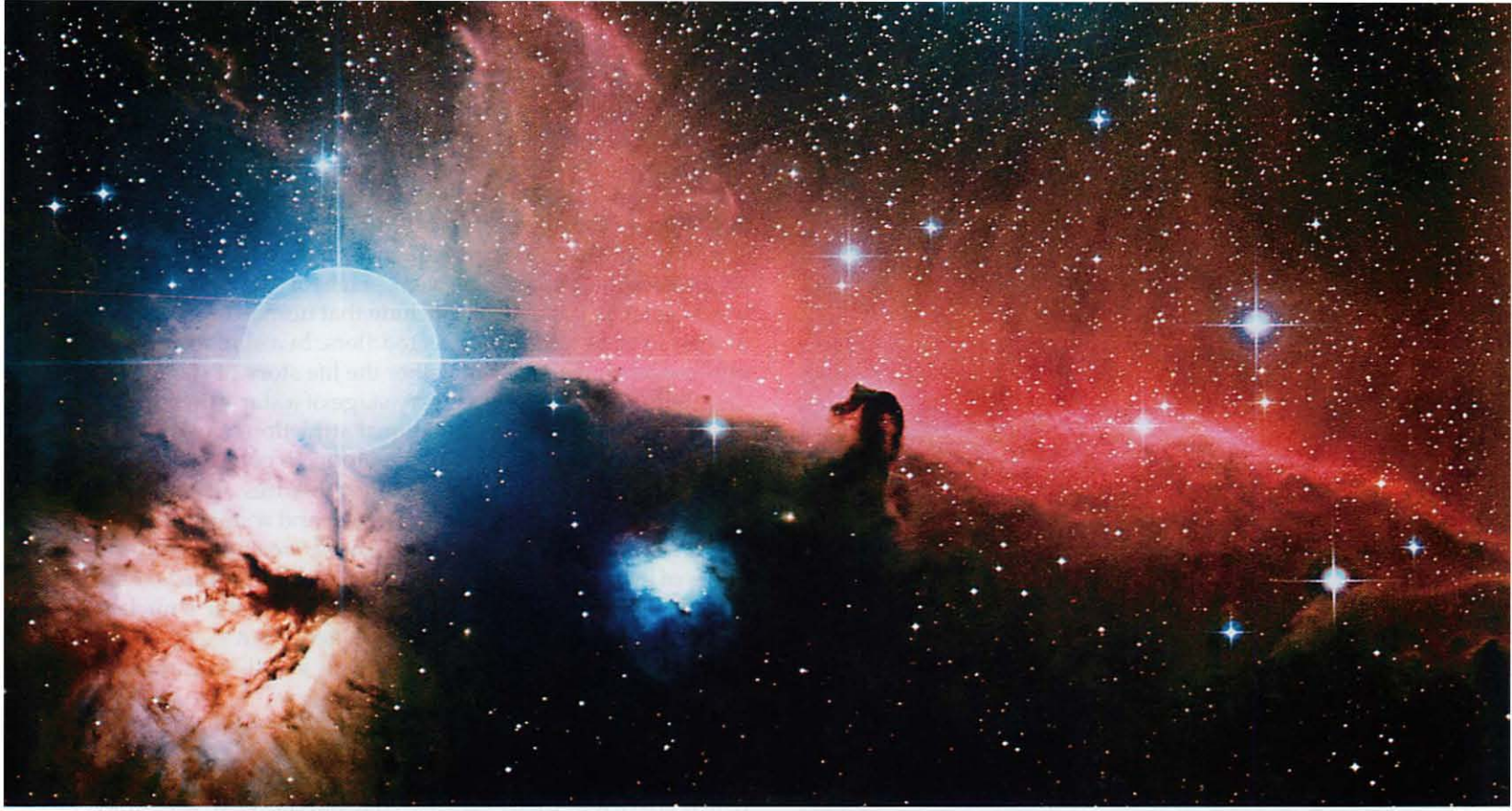


FIGURE 16.10 The Horsehead Nebula, a dark nebula in a region of glowing nebulosity in Orion. (© Anglo-Australian Observatory/Royal Observatory, photography by David Malin)

in an increase in the internal gas pressure. At some point, the increased atomic motion produces an outward force (pressure) that exactly balances the inward-directed force of gravity. When this balance is reached, the star becomes a *stable main-sequence star* (Figure 16.11). In other words, a main-sequence star is one in which the force of gravity, which is trying to squeeze the star into the smallest possible ball, is balanced by gas pressure created by hydrogen burning in the star's interior.

Main-Sequence Stage

During the main-sequence stage, the star experiences very little change in size or energy output. Hydrogen is continually being converted into helium, and the energy that is released keeps the gas pressure sufficiently high to prevent gravitational collapse. How long can the star maintain this balance? Hot, massive blue stars radiate energy at such an enormous rate that they substantially deplete their hydrogen fuel in only a few million years, approaching the end of their main-sequence stage rapidly. By contrast, the very smallest (red) main-sequence stars may take hundreds of billions of years to burn their hydrogen, living practically forever. A yellow star, such as the Sun, remains a main-sequence star for about 10 billion years before consuming most of its usable hydrogen fuel. Since the solar system is about 5 billion years old, the Sun will remain a stable main-sequence star for another 5 billion years.

The average star spends 90 percent of its life as a hydrogen-burning main-sequence star. Once the hydrogen fuel in the star's core is depleted, it will evolve rapidly and die. However, with the exception of the least-massive stars, death is delayed when another type of nuclear reaction is triggered and the star becomes a red giant.

Red Giant Stage

The evolution to the red giant stage begins when the usable hydrogen in the star's interior is consumed, leaving a helium-rich core. Although hydrogen fusion is still progressing in the star's outer shell, no fusion is taking place in the core. Without a source of energy, the core no longer has the gas pressure necessary to support itself against the inward force of gravity. As a result, the core begins to contract.

The collapse of the star's interior causes its temperature to rapidly increase as gravitational energy is converted into heat. Some of this energy is radiated outward, initiating a more vigorous level of hydrogen fusion in the star's outer shell. The additional energy from the accelerated rate of hydrogen burning heats and enormously expands the star's outer gaseous shell. The result is a bloated red giant hundreds, and occasionally even thousands, of times its main-sequence size (Figure 16.11).

As the star expands, its surface cools, which explains the star's red color—comparatively cool objects radiate more of their energy as long-wavelength radiation. Eventually the star's gravitational force stops this outward expansion and

the two opposing forces, gravity and gas pressure, are once again in balance. The star enters a stable state, only much larger in size. Some red giants overshoot the equilibrium point and then rebound like an overextended spring. Such stars continue to expand and contract, never reaching equilibrium. Instead, they become variable stars.

While the envelope of a red giant expands, the core continues to collapse and the internal temperature eventually reaches 100 million K. At this incredible temperature, it is hot enough to start a nuclear reaction in which helium is converted to carbon. At this point, a red giant consumes both hydrogen and helium to produce energy. In stars more massive than the Sun, other thermonuclear reactions are also triggered. The result is the generation of all the elements on the periodic table up to number 26, iron. Nuclear reactions that generate elements heavier than iron require an additional source of energy.

Eventually, all the usable nuclear fuel in a star will be consumed. The Sun, for example, will spend less than a billion years as a giant while more massive stars will pass through this stage even more rapidly. Once all the fuel is gone, the force of gravity will squeeze the star into the smallest, most dense piece of matter possible.

Burnout and Death

What happens to a star after the red giant phase? We know that a star, regardless of its size, must eventually exhaust all of its usable nuclear fuel and collapse in response to its immense gravitational field. Since the gravitational field of a star is dependent on its mass, low-mass stars have different fates than high-mass stars. With this in mind, we will consider the final stage for stars in three different mass categories.

Death of Low-Mass Stars

Stars less than one-half the mass of the Sun (0.5 solar mass) consume their fuel at a comparatively slow rate (**FIGURE 16.12A**). Consequently, these small, *cool red stars* may remain a main-sequence star for up to 100 billion years. Because the interior of a low-mass star never attains sufficiently high temperatures and pressures to fuse helium, its only energy source is hydrogen fusion. Thus, a low-mass star never evolves to become a bloated red giant. Rather, it remains a stable main-sequence star until it has consumed its usable hydrogen fuel and collapses into a hot, dense *white dwarf*. As you shall see, white dwarfs are small, compact objects unable to support hydrogen burning.

Death of Medium-Mass (Sun-like) Stars

All main-sequence stars with masses ranging between one-half to eight times that of the Sun evolve in essentially the same way (**FIGURE 16.12B**). During their giant phase, Sun-like stars fuse hydrogen and helium fuel at an accelerated rate. Once this fuel is exhausted, these stars (like low-mass stars) collapse into an Earth-size body of great density—a white dwarf. The gravitational energy supplied to a collapsing white dwarf is reflected in its high surface temperature, hence its white color. However, without a source of nuclear energy, a white dwarf becomes cooler and dimmer as it continually radiates its remaining thermal energy into space.

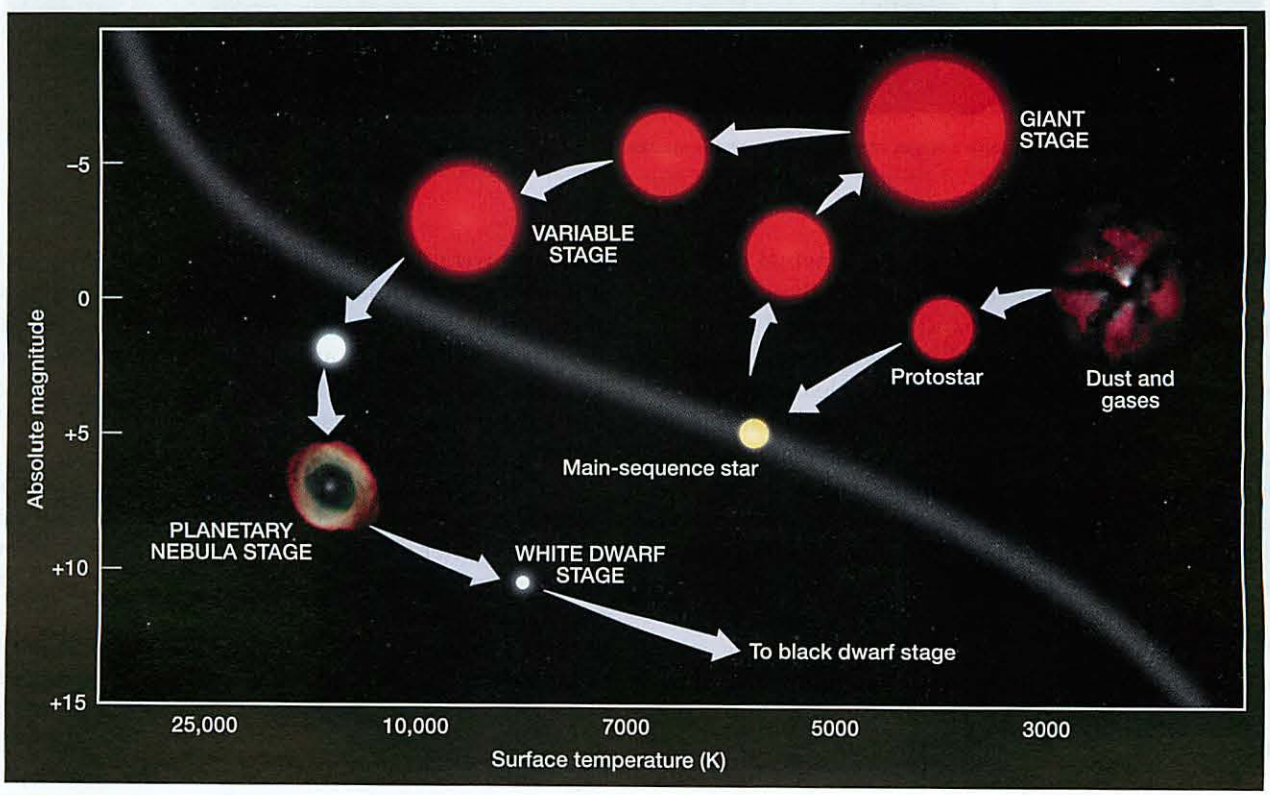


FIGURE 16.11 H-R diagram showing stellar evolution for a star about as massive as the Sun.

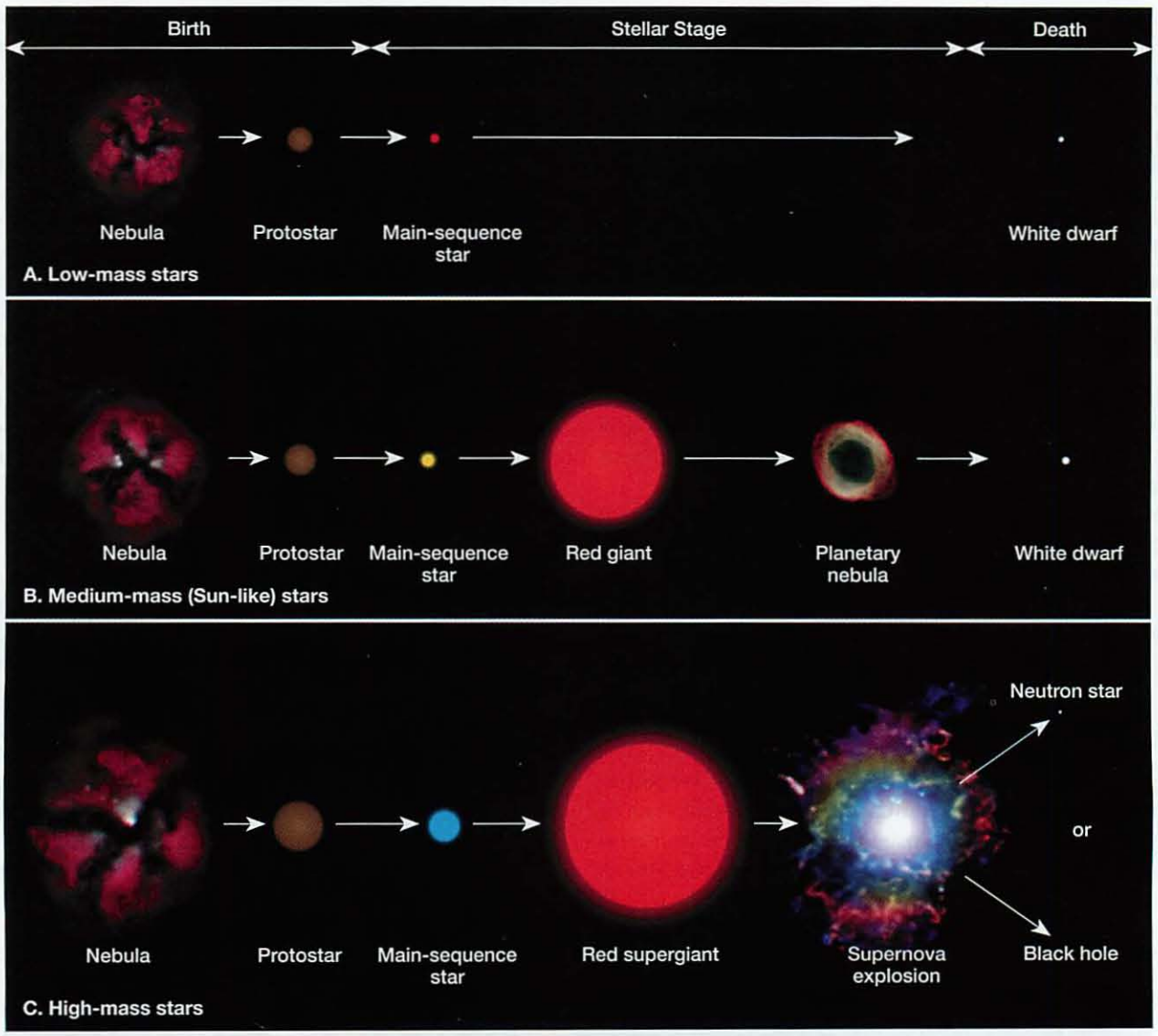


FIGURE 16.12 The evolutionary stages of stars having various masses.

During their collapse from red giants to white dwarfs, medium-mass stars are believed to cast off their bloated outer atmosphere, creating an expanding spherical cloud of gas. The remaining hot, central white dwarf heats the gas cloud, causing it to glow. These spectacular, gleaming spherical clouds are called **planetary nebulae**. A good example of a planetary nebula is the Helix Nebula in the constellation Aquarius (**FIGURE 16.13**). This nebula appears as a ring because our line of sight through the center traverses less gaseous material than at the nebula's edge. It is, nevertheless, spherical in shape.

Death of Massive Stars

In contrast to Sun-like stars, which expire nonviolently, stars exceeding eight solar masses have relatively short life spans and terminate in a brilliant explosion called a *supernova* (**FIGURE 16.12C**). During a supernova event, a star becomes millions of times brighter than its prenova stage. If one of the nearest stars to Earth produced such an outburst, its brilliance would surpass that of the Sun. Fortunately for us, supernovae are relatively rare events; none have been observed in our galaxy since the advent of the telescope, although Tycho Brahe and Kepler each recorded one about 30 years apart. An even brighter supernova was recorded in A.D. 1054 by the Chinese. Today, the remnant of this great outburst is the Crab nebula, shown in **FIGURE 16.14**.

A supernova event is likely triggered when a massive star has consumed most of its nuclear fuel. Without a heat engine to generate the gas pressure required to balance its immense gravitational field, it collapses. This implosion is cataclysmic, resulting in a shock wave that moves out from the star's interior. This energetic shock wave blasts the star's outer shell into space, generating the supernova event.

Theoretical work predicts that during a supernova, the star's interior condenses into a very hot object, possibly no larger than 20 kilometers in diameter. These incomprehensibly dense bodies have been named *neutron stars*. Some supernovae events are thought to produce even smaller and more

FIGURE 16.13 The Helix Nebula, the nearest planetary nebula to our solar system. A planetary nebula is the ejected outer envelope of a Sun-like star that formed during the star's collapse from a red giant to a white dwarf. (© Anglo-Australian Observatory, photography by David Malin)

Figure 16.11 shows the evolution of a star about the size of the Sun on an H-R diagram. Keep in mind that the star does not physically follow this path, but rather that its position on the H-R diagram represents the color (temperature) and absolute magnitude (brightness) of the star at various stages in its evolution.

Using the H-R diagram, the protostar that became the Sun would be located to the right and above the main sequence (Figure 16.11). It appears to the right because of its relatively cool surface temperature (red color), and above because it would be more luminous than a main-sequence star of the same color, because it is still a large collection of gas with a large surface area. As it shrinks and its nuclear furnace turns on, its surface gets hotter, turning yellow, and its total luminosity decreases because its total surface area is much smaller. You should be able to follow Figure 16.11 to visualize the remaining evolutionary changes experienced by a star the size of the Sun. In addition, Table 16.3 provides a summary of the evolutionary history of stars having various masses.

intriguing objects called *black holes*. We will consider the nature of neutron stars and black holes in the following section on stellar remnants.

H-R Diagrams and Stellar Evolution

Hertzsprung-Russell diagrams have been very helpful in formulating and testing models of stellar evolution. They are also useful for illustrating the changes that take place in an individual star during its life span.

DID YOU KNOW?

The first naked-eye supernova in 383 years was discovered in the southern sky in February 1987. This stellar explosion was officially named SN 1987A (SN stands for supernova, and 1987A indicates that it was the first supernova observed in 1987). Naked-eye supernovae are rare. Only a few have been recorded in historic times. Arab observers saw one in 1006, and the Chinese recorded one in 1054 at the present location of the Crab Nebula. In addition, the astronomer Tycho Brahe observed a supernova in 1572, and Kepler saw one shortly thereafter in 1604.

STELLAR REMNANTS

Eventually, all stars consume their nuclear fuel and collapse into one of three final forms—a *white dwarf*, *neutron star*, or *black hole*. How a star's life ends, and what final form it takes, depends largely on the star's mass. Generally, low- and medium-mass stars die nonviolently, whereas high-mass stars die catastrophically. The dividing line between these two dramatically different possibilities is approximately eight solar masses.

White Dwarfs

Once low- and medium-mass stars consume their remaining thermal fuel, gravity causes them to collapse into *white dwarfs*. These Earth-sized objects have a mass roughly equal to the Sun. Thus, their densities may be a million times greater than water. A spoonful of such matter would weigh several tons. Densities this great are possible only when electrons are displaced inward from their regular orbits around an atom's nucleus. Material in this state is called **degenerate matter**.

The atoms in degenerate matter have been squeezed together so tightly that the electrons are pushed very close to the nucleus. Electrical repulsion, between the negatively

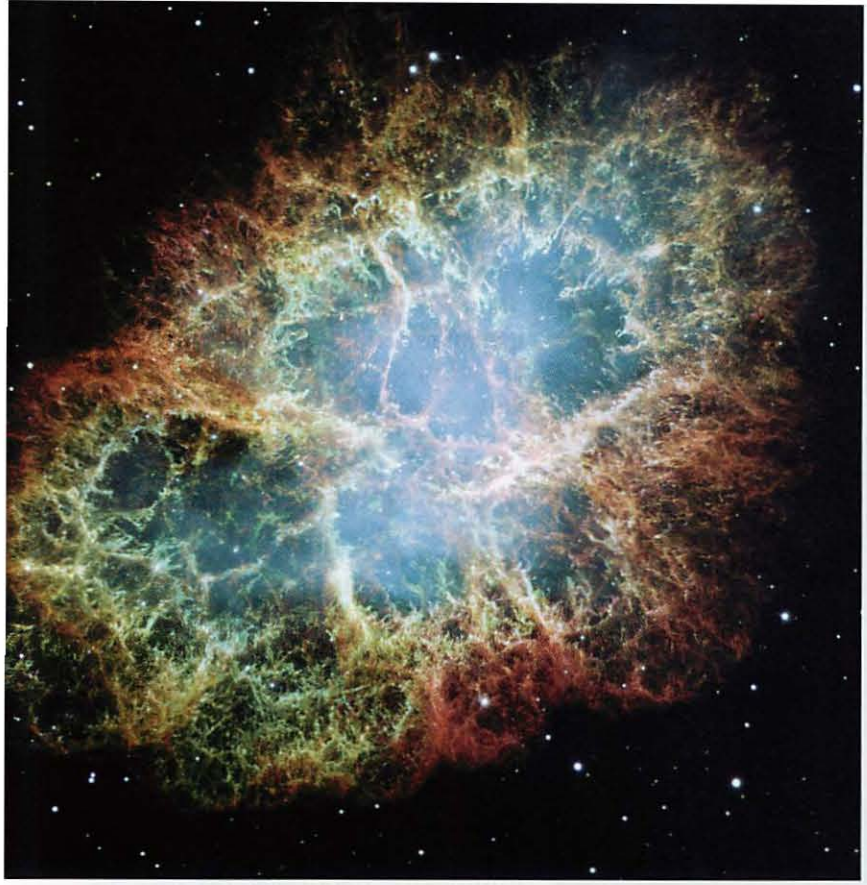


FIGURE 16.14 Crab Nebula in the constellation Taurus: the remains of the supernova of A.D. 1054. (NASA)

charged electrons and the positively charged nucleus, rather than molecular motion supports the star against even further gravitational collapse. Although atomic particles in degenerate matter are much closer together than in "normal" matter, they still are not packed as tightly as possible. Stars made of matter of an even greater density are known to exist.

As a main-sequence star contracts into a white dwarf, its surface becomes very hot, sometimes exceeding 25,000 K. Even so, without a source of energy, it slowly becomes cooler and dimmer. Eventually a white dwarf becomes a small, cold, burned-out ember in space called a *black dwarf*.

Neutron Stars

A study of white dwarfs produced what might appear to be a surprising conclusion. The *smallest white dwarfs* are the *most massive*, and the *largest* are the *least massive*. The explanation for this is that more massive stars, because of their greater gravitational fields, are squeezed into a smaller, more densely packed object than are less massive stars. Thus, the smallest white dwarfs were produced from the collapse of larger, more massive main-sequence stars than were the larger white dwarfs.

This conclusion led to the prediction that stars even smaller and more massive than white dwarfs must exist. Named **neutron stars**, these objects are the remnants of explosive supernova events. In a white dwarf, the electrons are pushed close to the nucleus, whereas in a neutron star the electrons are forced to combine with protons in the nucleus to produce neutrons (hence the name neutron star). If Earth were to collapse to the density of a neutron star, it would have a diameter equivalent to the length of a football field. A pea-size sample of this matter would weigh 100 million tons. This is approximately the density of an atomic nucleus; thus, a neutron star can be thought of as a large atomic nucleus, composed of only neutrons.

During a supernova implosion, the outer envelope of the star is ejected (**FIGURE 16.15**), and the core collapses into a very hot star about 20 kilometers (12.4 miles) in diameter. Although neutron stars have high surface temperatures, their small size greatly limits their luminosity, making them almost impossible to locate visually.

However, theoretical models predict that a neutron star would have a very strong magnetic field and a high rate of rotation. As a star collapses, it rotates faster, for the same reason ice skaters rotate faster as they pull in their arms. If the Sun were to collapse to the size of a neutron star, it would increase its rate of rotation from once every 25 days to nearly 1000 times per second. Radio waves generated by the rotating magnetic fields of a neutron star are concentrated into two narrow zones that align with the star's magnetic poles. Consequently, these stars resemble a rapidly rotating beacon emitting strong radio waves. If Earth happened to be in the path of these beacons, the star would appear to blink on and off, or pulsate, as the waves swept past.

In the early 1970s, a source that radiates short pulses of radio energy, named a **pulsar** (pulsating radio source), was discovered in the Crab Nebula. Visual inspection of this radio source indicated that it was a small star centered in the

Table 16.3 Summary of evolution for stars of various masses

Initial Mass of Main-Sequence Star (Sun = 1)*	Main-Sequence Stage	Giant Phase	Evolution After Giant Phase	Terminal State (Final Mass)
0.001	None (Planet)	No	Not applicable	Planet (0.001)
0.1	Red	No	Not applicable	White dwarf (0.1)
1–3	Yellow	Yes	Planetary Nebula	White dwarf (<1.4)
8	White	Yes	Supernova	Neutron star (1.4–3)
25	Blue	Yes (Supergiant)	Supernova	Black hole (>3.0)

*These mass numbers are estimates.

FIGURE 16.15 Veil Nebula in the constellation Cygnus is the remnant of an ancient supernova implosion. (Palomar Observatories/California Institute of Technology [Caltech])

nebula. The pulsar found in the Crab Nebula is very likely the remains of the supernova of A.D. 1054 (see Figure 16.14). Since then several other neutron stars have been discovered.

Black Holes

Although neutron stars are extremely dense, they are not the densest objects in the universe. Stellar evolutionary theory predicts that the mass of a neuron star cannot be greater than three times that of the Sun. Above this mass, not even tightly packed neutrons can withstand the star's gravitational pull. When the core of a star left behind after a supernova explosion exceeds the three-solar-mass limit, gravity wins the battle with pressure, and the stellar remnant collapses. (Although the precise figure is uncertain, the pre-supernova mass of such a star likely exceeded 25 solar masses.) The incredible object created by such a collapse is called a **black hole**.

Even though black holes are extremely hot, their surface gravity is so immense that even light cannot escape. Consequently, they literally disappear from sight. Anything that moves too close to a black hole will be swept in by its irresistible gravitational field and be devoured.

How did astronomers find objects whose gravitational field prevents the escape of all matter and energy? Theory predicts that as matter is pulled into a black hole, it should become very hot and emit a flood of x-rays before being engulfed. Because isolated black holes do not have a source of matter to engulf, astronomers decided to look at binary-star systems for evidence of matter being rapidly swept into a region of apparent nothingness.

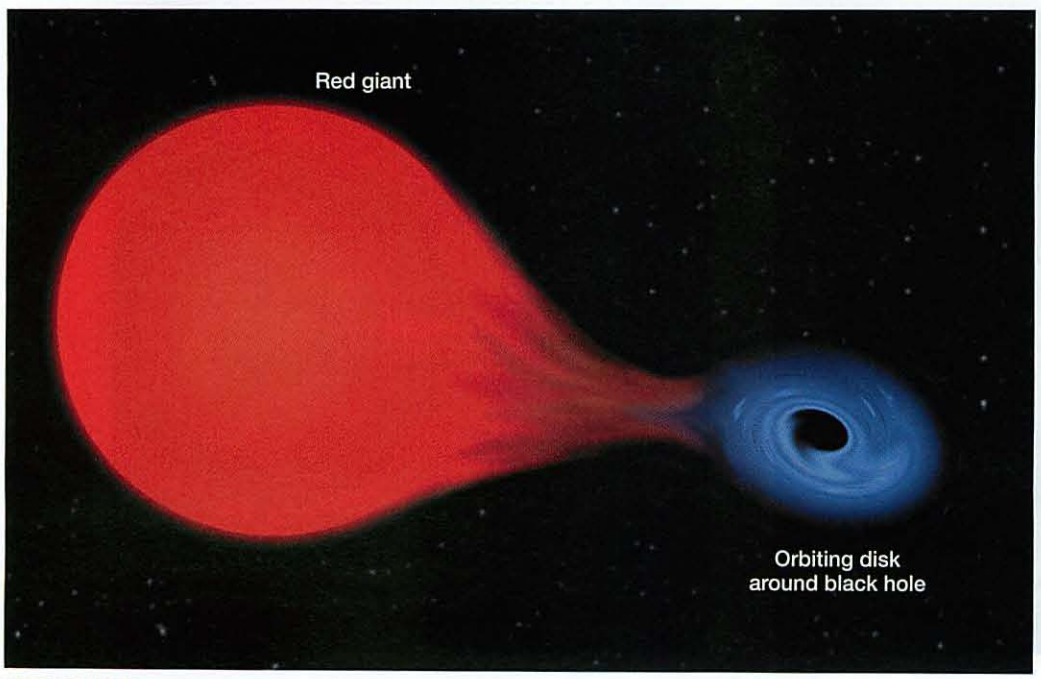


FIGURE 16.16 This illustration shows how astronomers suggest a binary pair consisting of a red giant and black hole might function.

A likely candidate for a black hole is Cygnus X-1, a strong x-ray source in the constellation Cygnus. This x-ray source can be detected orbiting a red supergiant companion once every 5.6 days. It appears that gases are pulled from the giant companion and spiral into a disc-shaped structure around a "void," thought to be a black hole (**FIGURE 16.16**). The result is the emission of a steady stream of x-rays. Because x-rays cannot penetrate our atmosphere efficiently, the existence of black holes was not confirmed until the advent of orbiting observatories. The first x-ray sources were discovered in 1971 by detectors on satellites, and soon after, Cygnus X-1 was determined to be a black hole.

FIGURE 16.17 Panorama of our galaxy, the Milky Way. Notice the dark band caused by the presence of interstellar dark nebulae. (Courtesy of Axel Mellinger)

THE MILKY WAY GALAXY

On a clear and moonless night away from city lights, you can see a truly marvelous sight—a band of light stretching from horizon to horizon. With his telescope, Galileo discovered that this band of light was composed of countless individual stars. Today, we realize that the Sun is actually a part of this vast system of stars, the Milky Way Galaxy (**FIGURE 16.17**).

The Milky Way is a spiral galaxy containing about 100 billion stars (**FIGURE 16.18A**). Its milky appearance is a result of the solar system's location within the flat galactic disk. When we look *along the plane* of the galaxy, we see a band of stars. You can see this in the edge-on view in **FIGURE 16.18B**. However, when we look *out of the plane* of the galaxy, we do not see as many stars.

When astronomers began to telescopically survey the stars located along the plane of the Milky Way, it appeared that equal numbers lay in every direction, and people wondered if Earth was actually at the center of the galaxy. It turns out the Earth is not in the center of the galaxy, and a simple illustration shows the fallacy of this argument. Imagine that the trees in an enormous forest represent the stars in the galaxy. After hiking into this forest a short distance, you look around. What you see is an equal number of trees in every direction. Are you really in the center of the forest? Not necessarily; from anywhere in the forest, except at the very edge, it will look as though you are in the middle.

Attempts to visually inspect the Milky Way are hindered by the large quantities of interstellar matter that lie in our line of sight. Nevertheless, with the aid of radio telescopes, the gross structure of our galaxy has been determined. The Milky Way is a relatively large spiral galaxy whose disk is about 100,000 light-years wide and about 10,000 light-years thick at the nucleus (Figure 16.18). As viewed from Earth, the center of the galaxy lies beyond the constellation Sagittarius.

Radio telescopes also show that the Milky Way has at least three distinct spiral arms. (**FIGURE 16.19**). The Sun is positioned in one of these arms about two-thirds of the way from the center, at a distance of about 30,000 light-years. The stars in the arms of the Milky Way rotate around the galactic nucleus, with the most outward ones moving the slowest, such that the ends of the arms appear to trail. The Sun takes about 200 million years to orbit around the galactic center.

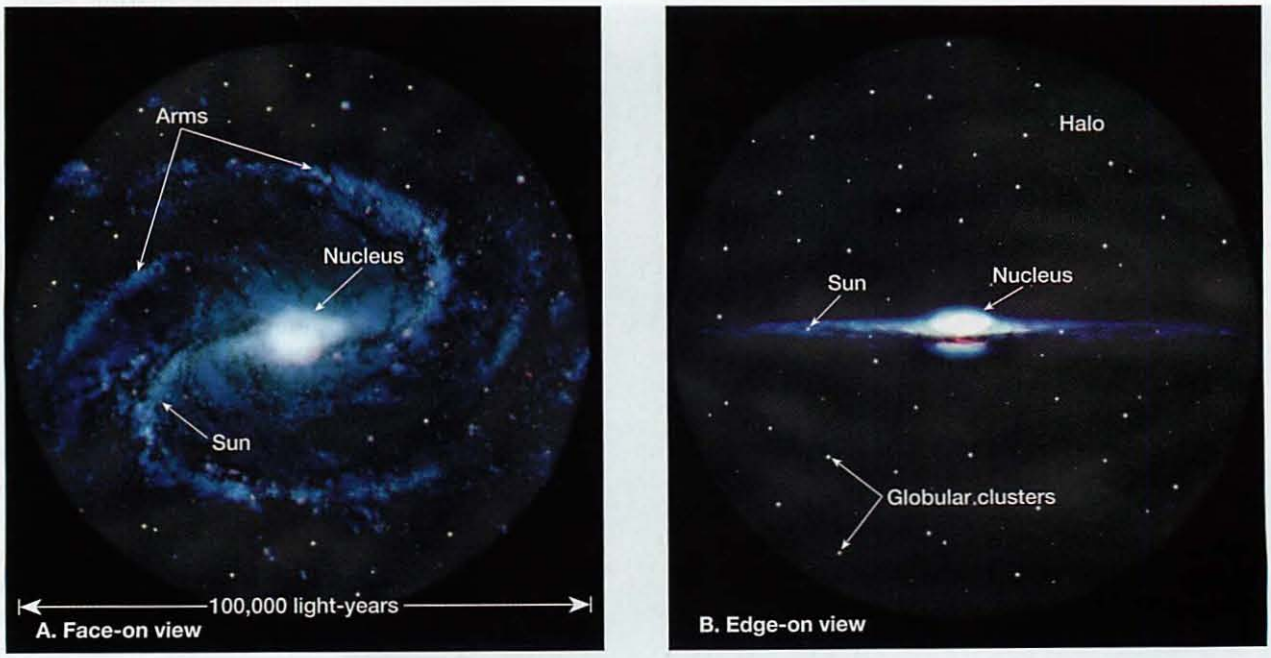


FIGURE 16.18 Structure of the visible portion of the Milky Way Galaxy.

FIGURE 16.19 If the Milky Way were photographed from a distance, it might appear like the spiral galaxy NGC 2997. (© Anglo-Australian Observatory, photography by David Malin)

Surrounding the galactic disk is a nearly spherical halo made of very tenuous gas and numerous globular clusters. These star clusters do not participate in the rotating motion of the arms but rather have their own orbits that carry them through the disk. Although some clusters are very dense, they pass among the stars of the galactic arms with plenty of room to spare.

NORMAL GALAXIES

In the mid-1700s, German philosopher Immanuel Kant proposed that the telescopically visible fuzzy patches of light scattered among the stars were actually distant galaxies like the Milky Way. Kant described them as island universes. Each galaxy, he believed, contained billions of stars and, as such, was a universe in itself. The weight of opinion, however, favored the hypothesis that they were dust and gas clouds (nebulae) within our galaxy because Earth was still considered a special and privileged place in the universe. Admitting that other galaxies existed would reduce Earth's (and humankind's) stature.

This matter was not resolved until the 1920s, when American astronomer Edwin Hubble was able to locate, within one of these fuzzy patches (the nebula in Andromeda), some unique stars that are known to be intrinsically very bright. Because these bright stars appeared to be faint when viewed telescopically, Hubble concluded that they must lie outside the Milky Way. The fuzzy patch Hubble observed lies more than two million light-years away and has been named the *Andromeda Galaxy* (**FIGURE 16.20**).

FIGURE 16.20 Andromeda Galaxy, a large spiral galaxy. A dwarf elliptical galaxy is located to the right of Andromeda. (NASA)

Hubble had extended the universe far beyond the limits of our imagination, to include hundreds of billions of galaxies, each containing hundreds of billions of stars. It has been said that a million galaxies are found in that portion of the sky bounded by the cup of the Big Dipper. There truly are more stars in the heavens than grains of sand in all the beaches on Earth.

Types of Galaxies

Among the hundreds of billions of galaxies, three basic types of *normal galaxies* have been identified: *spiral*, *elliptical*, and *irregular*. In addition, scattered throughout the universe, a few galaxies differ considerably from the norm. These very luminous objects are known collectively as *active galaxies*.

A.

B.

FIGURE 16.21 Two views illustrating the idealized structure of spiral galaxies. **A.** Spiral galaxy known as Messier 81, or M81. **B.** Edge-on view of a spiral galaxy captured by Hubble Space Telescope. (NASA)

Spiral Galaxies

The Milky Way and the Andromeda Galaxy are examples of large **spiral galaxies** (FIGURE 16.21). (Andromeda can be seen with the unaided eye as a fuzzy fifth-magnitude object.) Spiral galaxies are generally large, ranging from 20,000 to about 125,000 light-years in diameter. Typically, they are disk-shaped, with a greater concentration of stars near their centers, but there are numerous variations. Viewed broadside, arms are often seen extending from the central nucleus and sweeping gracefully away. The outermost stars of these arms rotate most slowly, giving the galaxy the appearance of a fireworks pinwheel.

One type of spiral galaxy, however, has the stars arranged in the shape of a bar, which rotates as a rigid system. This requires that the outer stars move faster than the inner ones, a fact not easily reconciled with the laws of motion. Attached to each end of these bars are curved spiral arms. These have become known as **barred spiral galaxies** (FIGURE 16.22). About 10 percent of all galaxies are thought to be barred spirals with another 20 percent regular spiral galaxies like the Milky Way.

FIGURE 16.22 Barred spiral galaxy. (NASA)

Elliptical Galaxies

The most numerous group, making up 60 percent of the total, are the **elliptical galaxies**. These are generally smaller than spiral galaxies. Some are so much smaller, in fact, that the term *dwarf galaxy* has been applied to them. Because these dwarf galaxies are not visible at great distances, a visual survey of the sky shows more of the conspicuous large spiral galaxies. However, if one looks at the galaxies in any given volume of the universe, elliptical galaxies are the most numerous.

Although most elliptical galaxies are small, the very largest known galaxies (200,000 light-years in diameter) are also elliptical. As their name implies, elliptical galaxies have an ellipsoidal shape that ranges to nearly spherical, and they lack spiral arms. The dwarf companion of Andromeda shown in Figure 16.20 is an elliptical galaxy.

Irregular Galaxies

Only 10 percent of the known galaxies show no symmetry and are classified as **irregular galaxies**. The best-known irregular galaxies, the

Large and Small Magellanic Clouds in the Southern Hemisphere, are easily visible with the unaided eye. Named after the explorer Ferdinand Magellan, who observed them when he circumnavigated Earth in 1520, they are our nearest galactic neighbors—only 150,000 light-years away.

One of the major differences among the galactic types is the age of the stars that make them up. The irregular galaxies are composed mostly of young stars, whereas the elliptical galaxies contain old stars. The Milky Way and other spiral galaxies consist of both young and old stars, with the youngest located in the arms.

Galactic Clusters

Once astronomers discovered that stars were associated in groups (galaxies), they set out to determine whether galaxies were also grouped or just randomly distributed throughout the universe. They found that galaxies are grouped into clusters (**FIGURE 16.23**). Some large **galactic clusters** contain thousands of galaxies. Our own, called the **Local Group**, contains at least 28 galaxies. Of these, 3 are spirals, 11 are irregulars, and 14 are ellipticals. Galactic clusters also reside in huge swarms called *superclusters*. From visual observations, it appears that superclusters may be the largest entities in the universe.

FIGURE 16.23 A cluster of galaxies located about 1 billion light-years from Earth. (Courtesy of NASA)

THE BIG BANG AND THE FATE OF THE UNIVERSE

The universe is more than simply a collection of dust clouds, stars, stellar remnants, and galaxies. It is an entity with its own properties. **Cosmology** is the branch of science that studies these properties, and cosmologists have developed a comprehensive theory about the nature of the universe. Some of the questions cosmologists try to answer with this theory include: Did the universe have a beginning? If so, how did it start? How did the universe evolve to its present state? How long has it been around and how long will it last?

These are basic questions that many cultures have asked, in one form or another. Modern cosmology addresses these important issues and helps us understand the universe we inhabit. Today, there is only one theory describing the birth and current state of the universe that is seriously considered by most scientists—*the big bang*. We will look at some of the evidence that led to the development of the big bang theory, one tested prediction that supports it, and one implication of this theory that is currently being tested.

The Expanding Universe

Before we can discuss the evidence suggesting that the universe is expanding, we have to examine how astronomers measure relative motion in the universe. Here on Earth, you can tell if something is approaching because it appears to grow larger as it approaches or smaller as it recedes. Most objects in the universe are so distant that their apparent size never changes. Instead, astronomers look at the changes in the wavelengths of light emitted by these bodies to determine relative motion.

You have probably noticed the change in pitch of an ambulance siren as it passes by. When it is approaching, the sound seems to have a higher pitch than if you were standing next to it, and when it is moving away, it seems to have a lower pitch. This effect, which occurs for all wave motion, including sound and light waves, was first explained by Christian Doppler in 1842 and is called the *Doppler effect*. The reason for the difference in pitch is that it takes time for the wave to be emitted. If the source of the wave is moving away, the beginning of the wave is emitted nearer to you than the end of the wave, "stretching" the wave and giving it a longer wavelength (**FIGURE 16.24**). For an approaching wave source, the wave is compressed.

In the case of light, when a source is moving away, the light we see is of lower energy than the originally emitted light (the light is shifted to the red end of the spectrum) because the emitted waves are lengthened. Approaching objects have their light waves shifted toward the blue end of the spectrum (shorter wavelength). Therefore, the Doppler effect reveals whether Earth and another celestial body are approaching one another or moving apart. In addition, the amount of shift allows us to determine the relative velocity between Earth and the object. Large Doppler shifts indicate high velocities; small Doppler shifts indicate low velocities.

One of the most important discoveries of modern astronomy was made in 1929 by Edwin Hubble. Using observational data collected several years earlier, Hubble showed that almost all galaxies have Doppler shifts toward the red end of the spectrum. The red shift occurs because the

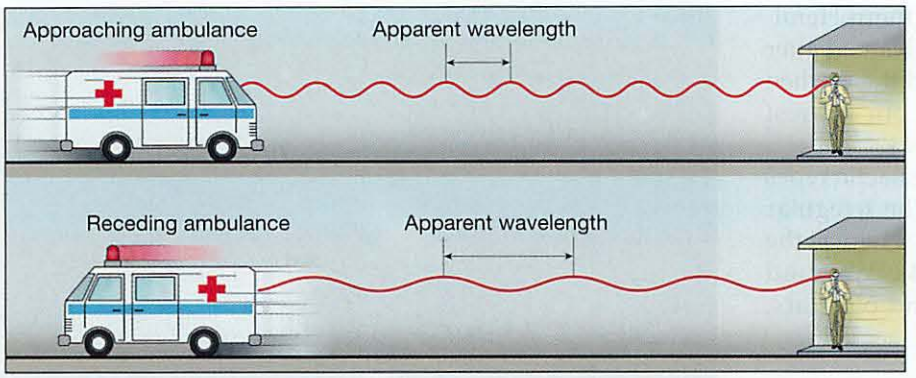


FIGURE 16.24 The Doppler effect, illustrating the apparent lengthening and shortening of wavelengths caused by the relative motion between a source and an observer.

light waves are "stretched," indicating that Earth and the source are moving away from each other (galaxies in the Local Group are an exception). Hubble set out to determine what the predominance of red shifts tells us about the universe.

Hubble realized that dimmer galaxies were probably farther away than brighter galaxies, so he tried to determine whether there was a relation between the distance to a galaxy and its red shift. Using estimated distances based on relative brightness, Hubble discovered that the red shifts of galaxies increase with distance and that the most distant galaxies are receding the fastest and at enormous speeds. This idea, termed **Hubble's law**, states that galaxies are receding from us at speeds that are proportional to their distances.

Hubble was surprised at this discovery because it implied that the most distant galaxies are moving away from us many times faster than those nearby. At the time, conventional wisdom was that the universe was unchanging. It had always existed much like it is now, and would continue to exist, relatively unchanged, indefinitely. What cosmological theory could explain Hubble's findings? It did not take long to realize that an expanding universe adequately accounts for the observed red shifts. The theory of the expanding universe states that new space is being created between objects that are very far apart (Earth and objects outside the Local Group of galaxies, for example).

To help visualize the nature of this expanding universe, we will employ a popular analogy. Imagine a loaf of raisin bread dough that has been set out to rise for a few hours (**FIGURE 16.25**). Also imagine that the raisins are galaxies and the dough is space. As the dough doubles in size, so does the distance between all of the raisins. In addition, the raisins that were originally farthest apart traveled a greater distance in the same time span than those located closer together. We therefore conclude that in an expanding universe, as in our analogy, those objects located farther apart move away from each other more rapidly.

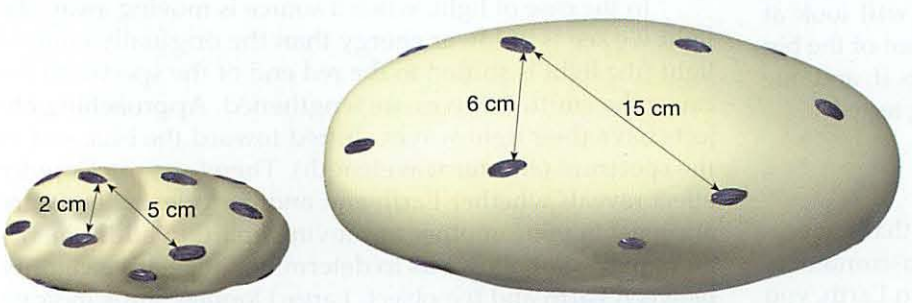
Another feature of the expanding universe can be demonstrated using the raisin bread analogy. No matter which raisin you select, it moves away from all the other raisins. Likewise, no matter where you are located in the universe, all the other galaxies (except those in the same cluster) will be receding from you. Edwin Hubble changed our understanding of the universe, and *The Hubble Space Telescope* is named in his honor.

The Origin of the Universe

First and foremost, any viable theory regarding the origin of the universe must account for the fact that all galaxies are moving away from us. Does this observation put our planet in the center of the universe? Probably not. Since all clusters of galaxies are moving away from all the other galactic groups, every point in the universe looks like the center of the universe just like every point in the forest looks like the center of the forest. In addition, if we are not in the center of our solar system or our galaxy, it is unlikely that we would be at the center of the universe. A more probable explanation exists: the expanding universe described above. If the universe is expanding, every galaxy would be moving away from every other galaxy.

The concept of an expanding universe has led to the widely accepted **big bang theory**. According to this theory, the entire universe was once confined to a dense, hot, supermassive point. Then, about 14 billion years ago, a cataclysmic explosion occurred, expanding the universe in all directions. The big bang marks the inception of the universe; everything in the universe was created at that instant. Some of the energy became matter that cooled and condensed, forming the stars that compose the galactic systems we now observe fleeing from their birthplace.

A good scientific theory makes predictions that can be tested. One prediction of the big bang theory is that if there was a cataclysmic explosion at the beginning of time, we should be able to detect the afterglow.



A. Raisin bread dough before it rises. **B. Raisin bread dough a few hours later.**

FIGURE 16.25 Illustration of the raisin bread analogy of an expanding universe. As the dough rises, raisins originally farther apart travel a greater distance in the same time span as those located closer together. Thus, raisins (like galaxies in a uniform expanding universe) that are located farther apart move away from each other more rapidly than those located nearer to each other.

DID YOU KNOW?

The name Big Bang was originally coined by cosmologist Fred Hoyle as a sarcastic comment on the believability of the theory. The Big Bang Theory proposes that our universe began as a violent explosion, from which the universe continues to expand, evolve, and cool. Through decades of experimentation and observation, scientists have gathered substantial evidence that supports this theory. Despite this fact, the Big Bang Theory, like all other scientific theories, can never be proved. It is always possible that a future observation will disprove a previously accepted theory. Nevertheless, the Big Bang has replaced all alternative theories and remains the only widely accepted scientific model for the origin of the universe.

Although the light released in the big bang had very high energy and very short wavelengths, the expansion of the universe should have stretched out the waves so that today they would be "seen" as long-wavelength radio waves. In 1965 this radiation was detected and found to fill the entire visible universe just as predicted. Most cosmologists consider this strong evidence for the big bang theory.

The End of the Universe

If the universe began with a big bang, how will it end? One possibility is that the universe will expand forever. In this scenario, the stars will slowly burn out, being replaced by invisible degenerate matter and black holes that travel outward through an endless, dark, cold universe. The other possibility is that the outward flight of the galaxies will slow and eventually stop due to gravity. Gravitational contraction would follow, causing the galaxies to eventually collide and coalesce into the high-energy, high-density mass from which the universe began. This fiery death of the universe, the big bang operating in reverse, has been called the "*big crunch.*"

Whether or not the universe will expand forever, or eventually collapse upon itself, depends on its average density. If the average density of the universe is more than an amount known as its *critical density* (about one atom for every cubic meter), gravitational attraction is sufficient to stop the outward expansion and cause the universe to collapse. On the other hand, if the density of the universe is less than the critical value, it will expand forever. Current estimates of the density of the universe place it below the critical density, which predicts an ever expanding, or *open universe.* Additional support for an open universe comes from studies that indicate the universe is expanding faster now than in the past. Hence, the view currently favored by most cosmologists is an expanding universe with no ending point.

However, the methods used to determine the density of the universe have substantial uncertainties. It is possible that previously undetected matter (dark matter) exists in great quantities in the universe. *Dark matter* may sound very mysterious, even sinister, but all that the term means is that there may be matter out there that does not interact with electromagnetic radiation. Recall that almost all the information about the universe comes to us as light. If there is a form of matter that does not interact with light, we cannot "see" it, and it would be dark. However, all is not lost. It is possible that dark matter will show itself by gravitational interactions with the type of matter that we are familiar with. Many astronomers are presently looking for these interactions. If there is enough dark matter in the universe, the universe could, in fact, collapse in the "big crunch." Consider the following phrase as astronomers search for dark matter—"*Absence of evidence is not evidence of absence.*"

THE CHAPTER IN REVIEW

- One method for determining the distance to a star is to use a measurement called *stellar parallax*, the extremely slight back-and-forth shifting in a nearby star's position due to the orbital motion of Earth. *The farther away a star is, the less its parallax.* A unit used to express stellar distance is the *light-year*, the distance light travels in a year, which is about 9.5 trillion kilometers (5.8 trillion miles).

- The intrinsic properties of stars include *brightness, color, temperature, mass,* and *size.* Three factors control the brightness of a star as seen from Earth: how big it is, how hot it is, and how far away it is. *Magnitude* is the measure of a star's brightness. *Apparent magnitude* is how bright a star appears when viewed from Earth. *Absolute magnitude* is the "true" brightness of a star if it were at a standard distance of about 32.6 light-years. The difference between the two magnitudes is directly related to a star's distance. Color is a manifestation of a star's temperature. Very hot stars (surface temperatures above 30,000 K) appear blue; red stars are much cooler (surface temperatures generally less than 3000 K). Stars with surface temperatures between 5000 and 6000 K appear yellow, like our Sun. The center of mass of orbiting *binary stars* (two stars revolving around a common center of mass under their mutual gravitational attraction) is used to determine the mass of the individual stars in a binary system.

- *Variable stars* fluctuate in brightness. Some, called *pulsating variables,* fluctuate regularly in brightness by expanding and contracting in size. When a star explosively brightens, it is called a *nova.* During the outburst, the outer layer of the star is ejected at high speed. After reaching maximum brightness in a few days, the nova slowly returns in a year or so to its original brightness.

- A *Hertzsprung-Russell diagram* is constructed by plotting the absolute magnitudes and temperatures of stars on a graph. A great deal about the sizes of stars can be learned

from H-R diagrams. Stars located in the upper-right position of an H-R diagram are called *giants*, luminous stars of large radius. *Supergiants* are very large. Very small *white dwarf* stars are located in the lower-central portion of an H-R diagram. Ninety percent of all stars, called *main-sequence stars*, are in a band that runs from the upper-left corner to the lower-right corner of an H-R diagram.

- New stars are born out of enormous accumulations of dust and gases, called *nebula*, that are scattered between existing stars. A *bright nebula* glows because the matter is close to a very hot (blue) star. The two main types of bright nebulae are *emission nebulae* (which derive their visible light from the fluorescence of the ultraviolet light from a star in or near the nebula) and *reflection nebulae* (relatively dense dust clouds in interstellar space that are illuminated by reflecting the light of nearby stars). When a nebula is not close enough to a bright star to be illuminated, it is referred to as a *dark nebula*.

- Stars are born when their nuclear furnaces are ignited by the unimaginable pressures and temperatures in collapsing nebulae. New stars not yet hot enough for nuclear fusion are called *protostars*. When collapse causes the core of a protostar to reach a temperature of at least 10 million K, the fusion of hydrogen nuclei into helium nuclei begins a process called *hydrogen burning*. The opposing forces acting on a star are *gravity* trying to contract it and *gas pressure* (*thermal nuclear energy*) trying to expand it. When the two forces are balanced, the star becomes a stable *main-sequence star*. When the hydrogen in a star's core is consumed, its outer envelope expands enormously and a *red giant* star, hundreds to thousands of times larger than its main-sequence size, forms. When all the usable nuclear fuel in these giants is exhausted and gravity takes over, the stellar remnant collapses into a small, dense body.

- The *final fate of a star is determined by its mass*. Stars with less than one-half the mass of the Sun collapse into hot, dense *white dwarf* stars. Medium-mass stars, like the Sun, become red giants, collapse, and end up as white dwarf stars, often surrounded by expanding spherical clouds of glowing gas called *planetary nebulae*. Massive stars terminate in a brilliant explosion called a *supernova*. Supernovae events can produce small, extremely dense *neutron stars*, composed entirely of subatomic particles called neutrons, or even smaller and more dense *black holes*, objects that have such immense gravity that light cannot escape their surface.

- The *Milky Way Galaxy* is a large, disk-shaped *spiral galaxy* about 100,000 light-years wide and about 10,000 light-years thick at the center. There are three distinct *spiral arms* of stars, with some showing splintering. The Sun is positioned in one of these arms about two-thirds of the way from the galactic center, at a distance of about 30,000 light-years. Surrounding the galactic disk is a nearly spherical halo made of very tenuous gas and numerous *globular clusters* (nearly spherically shaped groups of densely packed stars).

- The various types of galaxies include (1) *irregular galaxies*, which lack symmetry and account for only 10 percent of the known galaxies; (2) *spiral galaxies*, which are typically disk-shaped with a somewhat greater concentration of stars near their centers, often containing arms of stars extending from their central nucleus; and (3) *elliptical galaxies*, the most abundant type, which have an ellipsoidal shape that ranges to nearly spherical and that lack spiral arms.

- Galaxies are not randomly distributed throughout the universe. They are grouped in *galactic clusters*, some containing thousands of galaxies. Our own, called the *Local Group*, contains at least 28 galaxies.

- By applying the *Doppler effect* (the apparent change in wavelength of radiation caused by the motions of the source and the observer) to the light of galaxies, galactic motion can be determined. Most galaxies have Doppler shifts toward the red end of the spectrum, indicating increasing distance. The amount of Doppler shift is dependent on the velocity at which the object is moving. Because the most distant galaxies have the greatest red shifts, Edwin Hubble concluded in the early 1900s that they were retreating from us with greater recessional velocities than were more nearby galaxies. It was soon realized that an *expanding universe* can adequately account for the observed red shifts.

- The realizations that the universe is expanding led to the widely accepted *big bang theory*. According to this theory, the entire universe was at one time confined in a dense, hot, supermassive concentration. Almost 14 billion years ago, a cataclysmic explosion hurled this material in all directions, creating all matter and space. Eventually the ejected masses of gas cooled and condensed, forming the stellar systems we now observe fleeing from their place of origin.

KEY TERMS

absolute magnitude (p. 460)
apparent magnitude (p. 459)
barred spiral galaxy (p. 474)
big bang theory (p. 476)
black hole (p. 471)
bright nebula (p. 464)
cosmology (p. 475)
dark nebula (p. 465)
degenerate matter (p. 469)
elliptical galaxy (p. 474)
emission nebula (p. 464)
eruptive variables (p. 461)
galactic cluster (p. 475)
Hertzsprung-Russell (H-R) diagram (p. 462)
Hubble's law (p. 476)
hydrogen burning (p. 465)
interstellar dust (p. 464)
irregular galaxy (p. 474)
light-year (p. 459)
Local Group (p. 475)
magnitude (p. 459)
main-sequence stars (p. 462)
nebula (p. 464)
neutron star (p. 470)
nova (p. 461)
planetary nebula (p. 468)
protostar (p. 465)
pulsar (p. 470)
pulsating variables (p. 461)
red giant (p. 462)
reflection nebula (p. 464)
spiral galaxy (p. 474)
stellar parallax (p. 458)
supergiant (p. 463)
supernova (p. 461)
visual binary (p. 461)
white dwarf (p. 463)

QUESTIONS FOR REVIEW

1. How far away in light-years is our nearest stellar neighbor, Proxima Centauri? Convert your answer to kilometers.
2. What is the most basic method of determining stellar distances?
3. Explain the difference between a star's apparent and absolute magnitudes. Which one is an intrinsic property of a star?
4. Which star is the most luminous, one having an absolute magnitude of five, or one with an absolute magnitude of ten?
5. What information about a star can be determined from its color?
6. What color are the hottest stars? Medium-temperature stars like the Sun? Coolest stars?
7. Which property of a star can be determined from binary-star systems?
8. Make a generalization relating the mass and luminosity of main-sequence stars.
9. The disk of a star cannot be resolved telescopically. Explain the method that astronomers use to estimate the size of stars.
10. Where on an H-R diagram does a star spend most of its lifetime?
11. How does the Sun compare in size and brightness to other main-sequence stars?
12. What role does interstellar matter play in stellar evolution?
13. Compare a bright nebula and a dark nebula.
14. What element is the fuel for main-sequence stars?
15. What causes a star to become a giant?
16. Why are less massive stars thought to age more slowly than more massive stars, even though they have much less "fuel"?
17. Enumerate the steps thought to be involved in the evolution of Sun-like stars.
18. What is the final state of a low-mass (red) main-sequence star?
19. What is the final state of a medium-mass (Sun-like) star?
20. How do the "lives" of the most massive stars end? What are the two possible products of this event?
21. Describe the general structure of the Milky Way Galaxy.
22. Compare the three general types of galaxies.
23. Explain why astronomers consider elliptical galaxies more abundant than spiral galaxies, even though more spiral galaxies have been sighted.
24. How did Edwin Hubble determine that the Andromeda Galaxy is located beyond the Milky Way?
25. What evidence supports the big bang theory?

COMPANION WEBSITE

The *Foundations of Earth Science* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by the authors and other Earth science instructors, this site will help improve your understanding of Earth science. Visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the ebook and to chapter-specific web resources.
- **Visualize** and comprehend challenging topics using learning activities in *GEODe: Earth Science*.
- **Test** yourself with online quizzes.