Our Nearest Neighbors

The closest star to the Sun is called Proxima Centauri. It is part of a triple-star system (three stars orbiting one another, bound by gravity) known as the Alpha Centauri complex. Proxima Centauri has the largest known stellar parallax, 0.77″, meaning that it is about 1/0.77 = 1.3 pc away—about 270,000 AU, or 4.3 light-years. That's the *nearest* star to the Sun—at almost 300,000 times the Earth–Sun distance! This is a fairly typical interstellar distance in the Milky Way Galaxy.

Vast distances can sometimes be grasped by means of analogies. Imagine Earth as a grain of sand orbiting a golfball-sized Sun at a distance of 1 m. The nearest star, also a golfball-sized object, is then 270 *kilo*meters away. Except for the planets in our solar system, ranging in size from grains of sand to small marbles within 50 m of the "Sun," and the Kuiper belt and Oort cloud, trillions of tiny dust grains scattered over a volume 100 km across, nothing of consequence exists in the 270 km separating the Sun and the other star.

The next nearest neighbor to the Sun beyond the Alpha Centauri system is called Barnard's Star. Its parallax is 0.55″, so it lies at a distance of 1.8 pc, or 6.0 light-years—370 km in our model. All told, fewer than 100 stars lie within 5 pc (1000 km in our model) of the Sun. Such is the void of interstellar space. Figure 10.2 is a map of our nearest galactic neighbors—the 30 or so stars lying within 4 pc of Earth. *Discovery 10-1* (p. 285) describes how some of the stars in this figure got their peculiar names.

Ground-based images of stars are generally smeared out into a seeing disk of radius 1″ or so by turbulence in Earth's atmosphere. ∞ *(Sec. 3.3)* However, astronomers use special techniques to routinely measure stellar parallaxes of 0.03″ or less, corresponding to stars within about 30 pc (100 light-years) of Earth. Several thousand stars lie within this range, most of them of much lower luminosity than the Sun and invisible to the naked eye. Adaptive optics systems allow more accurate measurements of stellar positions, extending the parallax range to over 100 pc. ∞ *(Sec. 3.3)* In the 1990s, the European *Hipparcos* satellite expanded this range to well over 200 pc, encompassing nearly a million stars. Even so, almost all of the stars in our Galaxy are far more distant. Upcoming next-generation space missions will extend out to 25,000 pc, spanning our entire Galaxy and likely revolutionizing our knowledge of its structure.

Stellar Motion

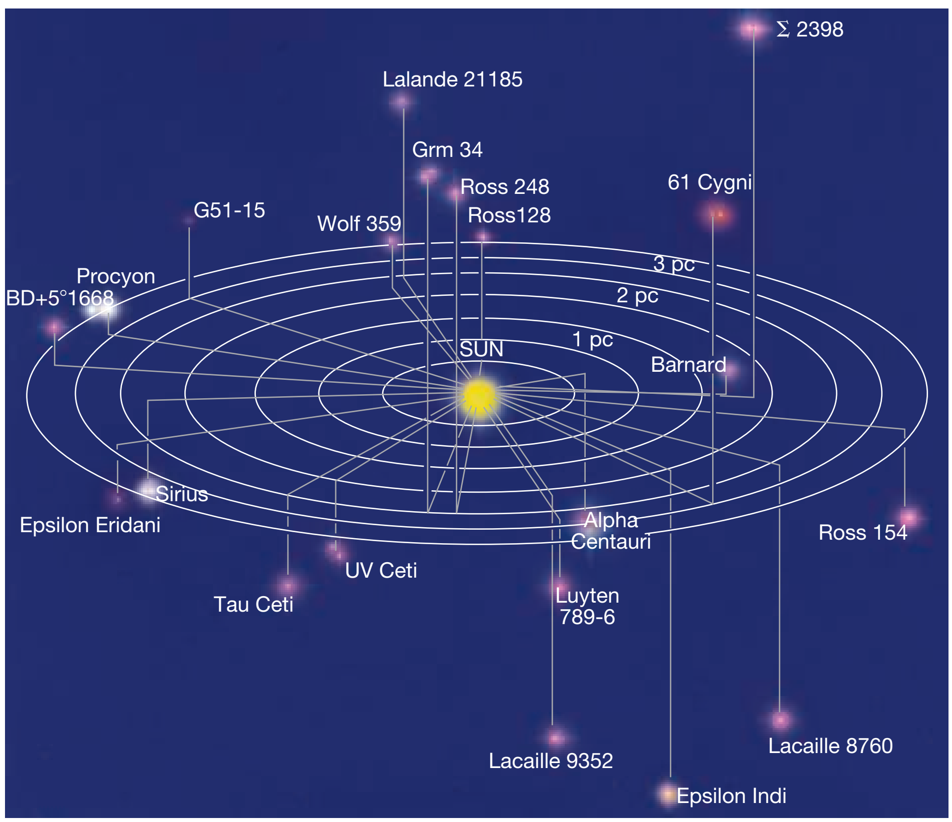
In addition to the apparent motion caused by parallax, stars have real spatial motion, too. A star's *radial* velocity—along the line of sight—can be measured using the Doppler effect. ∞ *(Sec. 2.7)* For many nearby stars the *transverse* velocity—perpendicular to our line of sight—can also be determined by careful monitoring of the star's position on the sky.

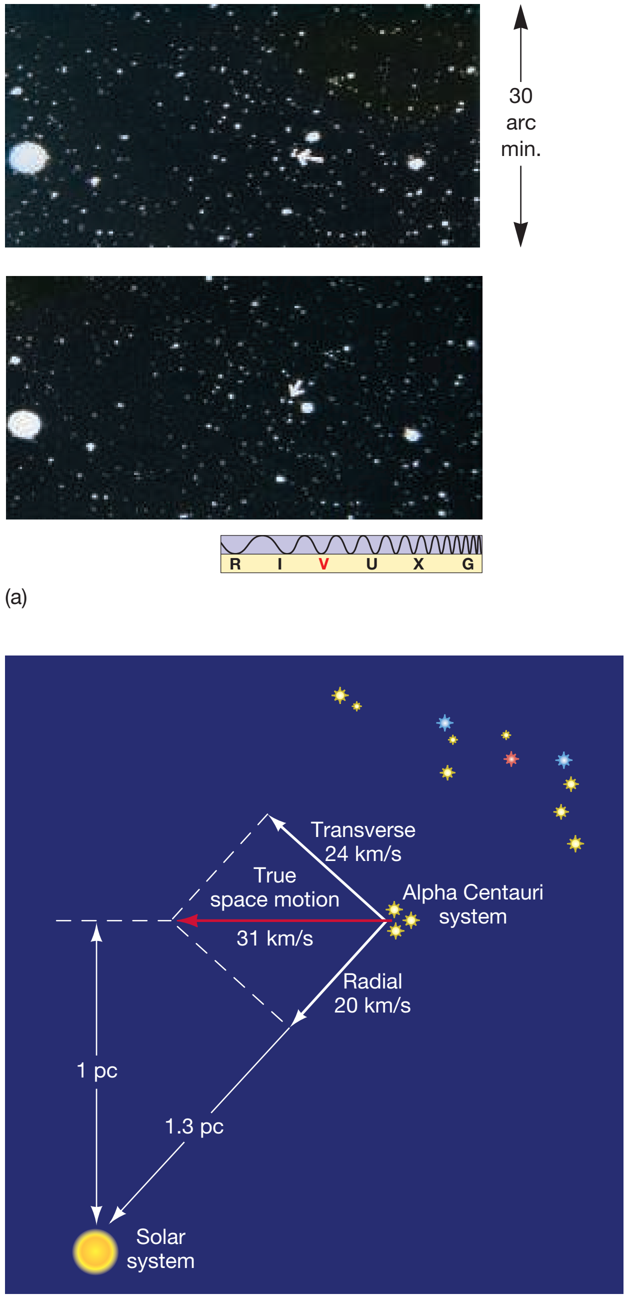
Figure 10.3(a) shows two photographs of the sky around Barnard's star, taken on the same day of the year, but 22 years apart. Note that the star (marked by the arrow) has moved during the 22-year interval shown. Because Earth was at the same point in its orbit when the photographs were taken, the observed displacement is *not* the result of parallax. Instead, it indicates *real* space motion of Barnard's star relative to the Sun. This annual

CONCEPT CHECK

Why can't astronomers use simultaneous observations from different parts of Earth's surface to determine stellar distances?

▼ **FIGURE 10.2 Sun's Neighborhood** A plot of the 30 closest stars to the Sun, projected so as to reveal their three-dimensional relationships. All lie within 4 pc (about 13 light-years) of Earth. The gridlines represent distances in the Galactic plane, and the vertical lines denote distances perpendicular to that plane.





◀ **FIGURE 10.3 Real Space Motion** (a) Comparison of two photographs taken 22 years apart shows real space motion for Barnard's star (denoted by an arrow). (b) The motion of the Alpha Centauri star system relative to our solar system. The radial component of the velocity is measured using the Doppler shift of lines in Alpha Centauri's spectrum. The transverse component is derived from the system's proper motion. The true spatial velocity, indicated by the red arrow, results from the combination of the two. *(Harvard College Observatory)*

movement of a star across the sky, as seen from Earth and corrected for parallax, is called **proper motion.** Barnard's star moved 228″ in 22 years. Its proper motion is therefore 228″/22 years, or 10.3″/yr.

A star's transverse velocity is easily calculated once its proper motion and its distance are known. At the distance of Barnard's star (1.8 pc), an angle of 10.3″ corresponds to a distance of 0.00009 pc, or about 2.8 billion kilometers. Barnard's star takes a year to travel this distance, so its transverse velocity is 2.8×10^9 km 3.2×10^7 s, or 88 km/s. Even though stars' transverse velocities are often quite large—tens or even hundreds of kilometers per second—their great distances from the Sun mean that it usually takes many years for us to discern their movement across the sky. In fact, Barnard's star has the largest-known proper motion of any star. Only a few hundred stars have proper motions greater than 1″/yr.

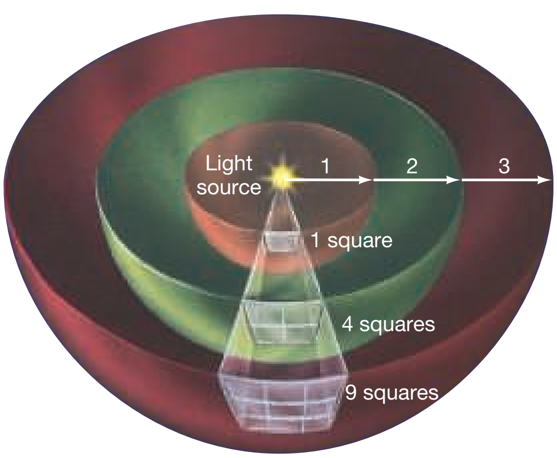
A star's total space velocity is the combination of its radial and transverse components. Figure 10.3(b) illustrates the relationship among these quantities for another near neighbor, Alpha Centauri. Spectral lines from Alpha Centauri are blueshifted by a tiny amount—about 0.0067 percent—allowing astronomers to measure the star system's radial velocity (relative to the Sun) as 300,000 km/s $\times$ 6.7 $\times\ 10^{-5}$ = 20 km/s toward us. ∞ ***(Sec. 2.7)*** Alpha Centauri's proper motion has been measured to be 3.7″/yr. At Alpha Centauri's distance of 1.35 pc (corresponding to a parallax of 0.74″), that measurement implies a transverse velocity of 24 km/s. We can combine the transverse (24 km/s) and radial (20 km/s) velocities according to the Pythagorean theorem, as indicated in the figure. The total velocity is $\sqrt{24^2 + 20^2}$ or about 31 km/s, in the direction shown by the horizontal red arrow.

10.2 Luminosity and Apparent Brightness

Luminosity—the amount of radiation leaving a star per unit time—is an *intrinsic* stellar property. ∞ ***(Sec 9.1)*** It does not depend in any way on the location or motion of the observer. It is sometimes referred to as the star's *absolute brightness*. However, when we observe a star, we see not its luminosity but rather its **apparent brightness**—the amount of energy striking unit area of some light-sensitive surface or device, such as a human eye or a CCD chip, per unit time. (Notice that this is precisely the same definition as given in Chapter 9 for the solar constant—in our new terminology, the solar constant is just the apparent brightness of the Sun.) In this section we discuss how these important quantities are related to one another.

Another Inverse-Square Law

Figure 10.4 shows light leaving a star and traveling through space. Moving outward, the radiation passes through imaginary spheres of increasing radius surrounding the source. The farther the light travels from the source, the less energy



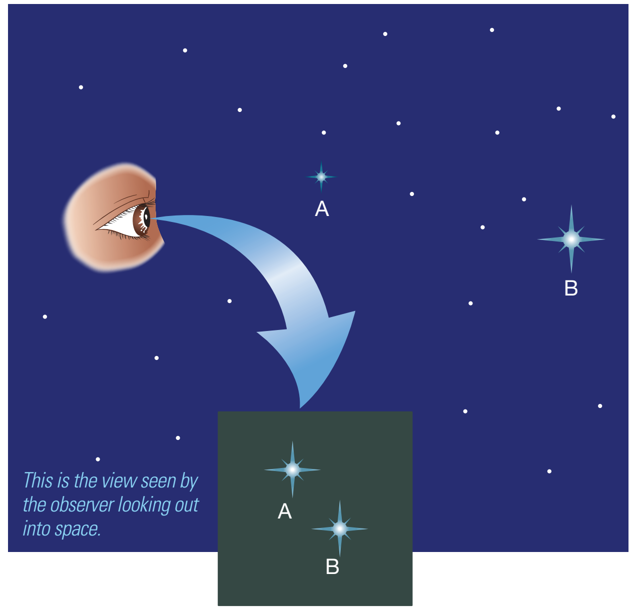
◀ **FIGURE 10.4 Inverse-Square Law** As light moves away from a source such as a star, it steadily dilutes while spreading over progressively larger surface areas (depicted here as sections of spherical shells). Thus, the amount of radiation received by a detector (the source's apparent brightness) varies inversely as the square of its distance from the source.

passes through each unit of area. Think of the energy as being spread out over an ever larger area and therefore spread more thinly, or "diluted," as it expands into space. Because the area of a sphere grows as the square of the radius, the energy per unit area—the star's apparent brightness—is inversely proportional to the square of the distance from the star. Doubling the distance from a star makes it appear 2^2, or 4, times fainter. Tripling the distance reduces the apparent brightness by a factor of 3^2, or 9, and so on.

Of course, the star's luminosity also affects its apparent brightness. Doubling the luminosity doubles the energy crossing any spherical shell surrounding the star and hence doubles the apparent brightness. The apparent brightness of a star is therefore directly proportional to the star's luminosity and inversely proportional to the square of its distance:

$$\text{apparent brightness} \propto \frac{\text{luminosity}}{\text{distance}^2}.$$

(Reminder: $\propto$ is the symbol representing proportionality.) Thus, two identical stars can have the same apparent brightness if (and only if) they lie at the same distance from Earth. However, as illustrated in Figure 10.5, two nonidentical stars can also have the same apparent brightness if the more luminous one lies farther away. A bright star, having large apparent brightness, is a powerful emitter of radiation (high luminosity), is near Earth, or both. A faint star (small apparent brightness) is a weak emitter (low luminosity), is far from Earth, or both.



▲ **FIGURE 10.5 Luminosity** Two stars A and B of different luminosities can appear equally bright to an observer on Earth if the brighter star B is more distant than the fainter star A.

10.1 DISCOVERY

Naming the Stars

Looking at Figure 10.2, you might well wonder how those stars got their names. In fact, there is no coherent convention for naming stars—or rather, there are many, often leading to many names for any given object! Here is a brief (and roughly chronological) description of some common naming schemes:

1. The brightest stars in the sky usually have ancient names. Many of the names are of Arabic origin, dating back to around the 10th century A.D., when Muslim astronomy flourished, preserving the scientific knowledge of Greek and other early cultures while European science floundered in the Dark Ages. Examples are Betelgeuse (*Yad al Jauzah,* Hand of the Central One, later corrupted to Bed Elgueze), Rigel (*Rijl Jauzah al Yusra,* Left Foot of the Central One), Aldebaran (*Al Dabaran,* the Follower), and Deneb (*Al Dhanab al Dulfin,* the Dolphin's Tail). The names Procyon and Sirius (see Figure 10.2) are Greek.
2. A more systematic scheme was introduced in 1603 by German lawyer Johann Bayer. He ranked the stars in a given constellation (Orion, say) by brightness, labeling them with Greek letters: Alpha Orionis (Betelgeuse), Beta Orionis (Rigel), or Epsilon Eridani (Figure 10.2). ∞ ***(Sec. 0.1)***
3. There are only 24 Greek letters, so eventually the Bayer scheme broke down. In the early 18th century, British Astronomer Royal John Flamsteed suggested simply numbering the stars from west to east within a constellation. In Flamsteeds scheme, Betelgeuse is 58 Ori, Rigel is 19 Ori, and so on (see also 61 Cygni in Figure 10.2). Sometimes the Bayer and Flamsteed designations are combined, as in "58 α Ori."
4. As telescopes improved and more and more stars were discovered, astronomers started compiling their own catalogs. Some catalogs listed stars by celestial coordinates—for example, star BD + 5°1668 in Figure 10.2, which appears in the 19th-century German Bonner Durchmusterung (BD) catalog and lies just over 5° above the celestial equator. ∞ ***(Sec. 0.1)*** Other catalogs simply named stars by the order in which they were added to the list—the star Lalande 21185 in Figure 10.2 is the 21,185th entry in a catalog compiled by 18th-century French astronomer Joseph de Lalande. Unfortunately, the catalogs often overlap, so stars can appear in many different catalogs with very different names. For example, Lalande 21185 is also known as HD 95735 (in the Henry Draper catalog), while Betelgeuse is also known as HD 39801 and SAO 113271 (in the Smithsonian Astrophysical Observatory).
5. Today, newly discovered stars are defined simply by their coordinates in the sky and not given any special name. If you like, you can (for a fee, of course) register your own star name, but don't expect any astronomer ever to cite that name, or to take the registry seriously—only "official" names approved by *International Astronomical Union* are used in astronomy.

DATA POINTS

Luminosity and Apparent Brightness

Forty-six percent of students had difficulty putting the inverse-square law into practice when discussing the apparent brightnesses of stars. Some points to remember:

- The apparent brightness of a star is directly proportional to its luminosity (which measures its true energy emission). Doubling the luminosity doubles the apparent brightness.
- The apparent brightness of a star is inversely proportional to the square of its distance. Doubling the distance decreases the apparent brightness by a factor of four.
- If two stars appear equally bright, the more luminous one is the more distant.

Determining a star's luminosity is a twofold task. First, the astronomer must determine the star's apparent brightness by measuring the amount of energy detected through a telescope in a given amount of time. Second, the star's distance must be measured—by parallax for nearby stars and by other means (to be discussed later) for more distant stars. The luminosity can then be found using the inverse-square law. This is the same reasoning used earlier in our discussion of how astronomers measure the luminosity of the Sun. ∞ *(Sec. 9.1)*

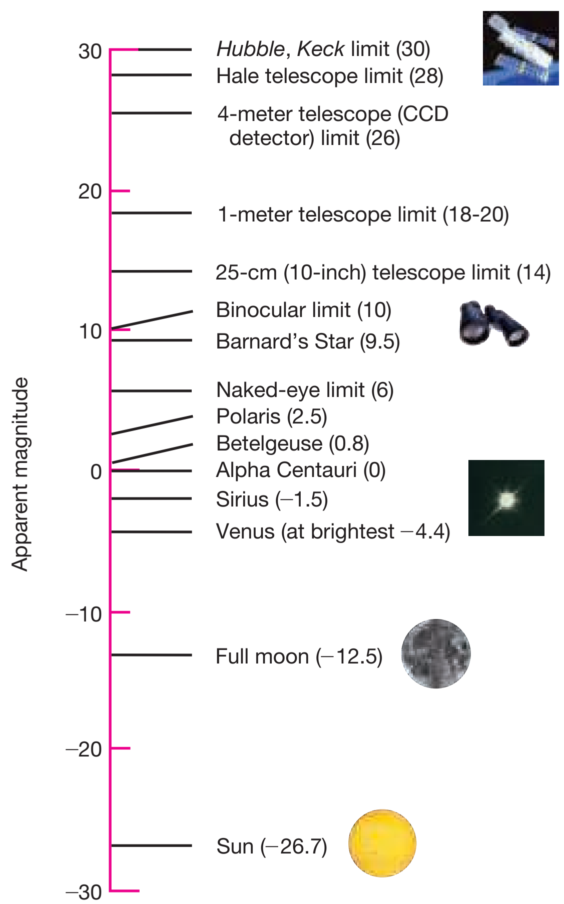
The Magnitude Scale

Instead of measuring apparent brightness in SI units (for example, watts per square meter, W/m^2, the unit in which we expressed the solar constant in Section 9.1), optical astronomers find it more convenient to work in terms of a construct called the **magnitude scale**—a system of ranking stars by their apparent brightness. This scale dates back to the second century B.C., when the Greek astronomer Hipparchus ranked the naked-eye stars into six groups. He categorized the brightest stars as first magnitude, labeled the next brightest stars as second magnitude, and so on, down to the faintest stars visible to the naked eye, which he classified as sixth magnitude. The range 1 (brightest) through 6 (faintest) spanned all the stars known to the ancients. Notice that a *large* magnitude means a *faint* star.

When astronomers began using telescopes with sophisticated detectors to measure the light received from stars, they quickly discovered two important facts about the magnitude scale. First, the 1 through 6 magnitude range defined by Hipparchus spans about a factor of 100 in apparent brightness—a first-magnitude star is approximately 100 times brighter than a sixth-magnitude star. Second, the characteristics of the human eye are such that a change of one magnitude corresponds to a factor of about 2.5 in apparent brightness. In other words, to the human eye a first-magnitude star is roughly 2.5 times brighter than a second-magnitude star, which in turn is roughly 2.5 times brighter than a third-magnitude star, and so on. By combining factors of 2.5, we confirm that a first-magnitude star is $(2.5)^5$, or roughly 100 times brighter than a sixth-magnitude star.

Because we are really talking about apparent (rather than absolute) brightnesses, astronomers refer to the numbers in Hipparchus's ranking system as **apparent magnitudes.** In the modern version of the magnitude scale, we *define* a change of 5 in the magnitude of an object to correspond to *exactly* a factor of 100 in apparent brightness. In addition, the scale is no longer limited to whole numbers and has expanded to include magnitudes outside the original range of 1 to 6. Very bright objects can have apparent magnitudes less than 1, and very faint objects can have apparent magnitudes much greater than 6. Figure 10.6 illustrates the apparent magnitudes of some astronomical objects, ranging from the Sun at − 26.8 to the faintest object detectable by the *Hubble* or *Keck* telescopes, at an apparent magnitude of + 30—about as faint as a firefly seen from a distance equal to Earth's diameter.

Apparent magnitude measures a star's apparent brightness when seen at the star's actual distance from us. To compare intrinsic, or absolute, properties of stars, however, astronomers imagine looking at all stars from a standard distance of 10 pc. (There is no particular reason to use 10 pc—it is simply convenient.) A star's **absolute magnitude** is its apparent magnitude when viewed from a distance of 10 pc. Because distance is fixed in this definition, absolute magnitude is a measure of a star's absolute brightness, or luminosity. Despite the Sun's large negative (that is, very bright) apparent magnitude, our star's absolute magnitude is 4.8. In other words, if the Sun were moved to a distance of 10 pc from Earth, it would be only a little brighter than the faintest stars visible in the night sky. As discussed further in *More Precisely 10-1*, the numerical difference between a star's absolute and apparent magnitudes is a measure of the distance to the star.



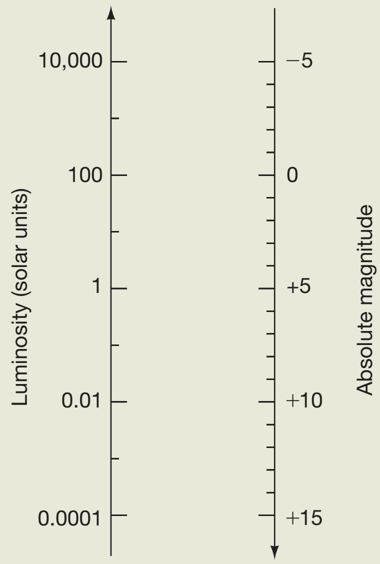
▲ **FIGURE 10.6 Apparent Magnitude** This graph illustrates the apparent magnitudes of some astronomical objects and the limiting magnitudes (that is, the faintest magnitudes attainable) of some telescopes used to observe them.

10.1 MORE PRECISELY

More on the Magnitude Scale

Let's restate our discussion of two important topics—stellar luminosity and the inverse-square law—in terms of magnitudes.

Absolute magnitude is equivalent to luminosity—an intrinsic property of a star. Given that the Sun's absolute magnitude is 4.8, we can construct a conversion chart (shown at right) relating these two quantities. Since an increase in brightness by a factor of 100 corresponds to a decrease in magnitude by 5 units, it follows that a star with luminosity 100 times that of the Sun has absolute magnitude $4.8 - 5 = -0.2$, while a 0.01-solar luminosity star has absolute magnitude $4.8 + 5 = 9.8$. We can fill in the gaps by noting that 1 magnitude corresponds to a factor of $100^{1/5} \approx 2.512$, 2 magnitudes to $100^{2/5} \approx 6.310$, and so on. A factor of 10 in brightness corresponds to 2.5 magnitudes. You can use this chart to convert between solar luminosities and absolute magnitudes in many of the figures in this and later chapters.



To cast the *inverse-square law* in these terms, recall that increasing the distance to a star by a factor of 10 decreases its apparent brightness by a factor of 100 (by the inverse-square law) and hence increases its apparent magnitude by 5 units. Increasing the distance by a factor of 100 increases the apparent magnitude by 10, and so on. Every increase in distance by a factor of 10 increases the apparent magnitude by 5. Since absolute magnitude is simply apparent magnitude at a distance of 10 pc, we can write:

$$\text{apparent magnitude} - \text{absolute magnitude} = 5 \log_{10}\left(\frac{\text{distance}}{10 \text{ pc}}\right).$$

(The *logarithm* function—the LOG key on your calculator—is defined by the property that if $a = \log_{10}(b)$, then $b = 10a$.) Even though it doesn't look much like it, this equation is precisely equivalent to the inverse-square law presented in the text!

For stars more than 10 pc from Earth, the apparent magnitude is greater than the absolute magnitude, while the reverse is true for stars closer than 10 pc. Thus, for example, the Sun, with an absolute magnitude of 4.8, seen from a distance of 100 pc would have an apparent magnitude of $4.8 + 5 \log_{10}(100) = 14.8$, since $\log_{10}(100) = 2$. This is well below the threshold of visibility for binoculars or even a large amateur telescope (see Figure 10.6). We can also turn this around to illustrate how knowledge of a star's absolute and apparent magnitudes tells us its distance. The star Rigel Kentaurus (also known as Alpha Centauri) has absolute magnitude + 4.34 and is observed to have apparent magnitude −0.01. Its magnitude difference is −4.35, and its distance must therefore be $10 \text{ pc} \times 10^{-4.34/5} = 1.35$ pc, in agreement with the result (obtained by parallax) given in the text.

10.3 Stellar Temperatures

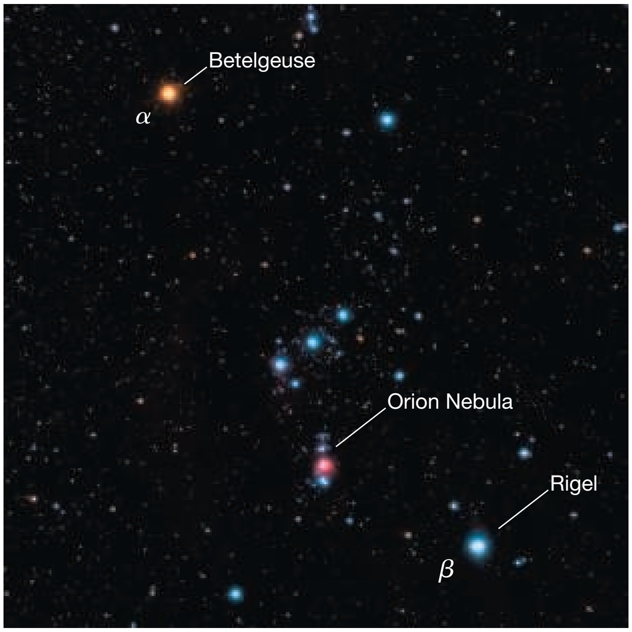
Color and the Blackbody Curve

Looking at the night sky, you can tell at a glance which stars are hot and which are cool. In Figure 10.7(a), which shows the constellation Orion as it appears through a small telescope, the colors of the cool red star Betelgeuse (α) and the hot blue star Rigel (β) are clearly evident. ∞ *(Sec. 0.2)* Astronomers can determine a star's surface temperature by measuring its apparent brightness (radiation intensity) at several frequencies, then matching the observations to the appropriate blackbody curve. ∞ *(Sec. 2.4)* In the case of the Sun, the theoretical curve that best fits the emission describes a 5800-K emitter. The same technique works for any star, regardless of its distance from Earth.

Because the basic shape of the blackbody curve is so well understood, astronomers can estimate a star's temperature using as few as *two* measurements at selected wavelengths. This is accomplished by using telescope filters that block out all radiation except that within specific wavelength ranges. For example, a B

CONCEPT CHECK

Two stars are observed to have the same apparent magnitude. Based on this information, what, if anything, can be said about their luminosities?



(a)

(b)

▲ **FIGURE 10.7 Star Colors** (a) The different colors of the stars composing the constellation Orion are easily distinguished in this photograph. The bright red star at the upper left (α) is Betelgeuse; the bright blue-white star at the lower right (*β*) is Rigel. The scale of this photograph is about 20° across. (b) An incredibly rich field of colorful stars, this time in the direction of the center of the Milky Way. Here, the field of view is just 2 arc minutes across—much smaller than in (a). *(P. Sanz/Alamy; NASA)*

(blue) filter rejects all radiation except for a certain range of violet to blue light. Similarly, a V (visual) filter passes only radiation in the green to yellow range (the part of the spectrum to which human eyes happen to be particularly sensitive).

Figure 10.8 shows how these filters admit different amounts of light for objects of different temperatures. In curve (a), corresponding to a very hot 30,000-K emitter, considerably more radiation is received through the B filter than through the V filter. The temperature of the emitter in curve (b) is 10,000 K, and the B and V intensities are about the same. The cool 3000-K emitter represented in curve (c) produces far more energy in the V range than in the B range. In each case it is possible to reconstruct the entire blackbody curve on the basis of only those two measurements because no other blackbody curve can be drawn through both measured points.

To the extent that a star's spectrum is well approximated as a blackbody, measurements of the B and V intensities are enough to specify the star's blackbody curve and thus yield its surface temperature. Astronomers often refer to the ratio of a star's B to V intensities (or, equivalently, the difference between the star's apparent magnitudes measured through the B and V filters) as the star's *color index* (or just its "color"). Table 10.1 lists surface temperatures and colors for a few well-known stars.

Stellar Spectra

Color is a useful way to describe a star, but astronomers often use a more detailed scheme to classify stellar properties, incorporating additional knowledge of stellar physics obtained through spectroscopy. ∞ *(Sec. 2.5)* Figure 10.9 compares the spectra of seven stars, arranged in order of decreasing surface temperature. All the spectra extend from 400 to 650 nm. Like the solar spectrum, each shows a series of dark absorption lines superimposed on a background of continuous color. ∞ *(Sec. 9.3)* However, the line patterns differ greatly from one star to another. Some stars display strong (prominent) lines in the long-wavelength part of the spectrum, while others have their strongest lines at short wavelengths. Still others show strong absorption lines spread across the whole visible spectrum. What do these differences tell us?

Although spectral lines of many elements are present at widely varying strengths, the differences among the spectra in Figure 10.9 are not due to differences in chemical composition—all seven stars are, in fact, more or less solar in their makeup. Instead, the differences are due almost entirely to the stars' temperatures. The spectrum at the top of Figure 10.9 is exactly what we expect from a star having solar composition and a surface temperature of about 30,000 K, the second from a 20,000-K star, and so on, down to the 3000-K star at the bottom.

The main differences among the spectra in Figure 10.9 are as follows:

- Spectra of stars having surface temperatures exceeding 25,000 K usually show *strong* absorption lines of singly ionized helium (i.e., helium atoms that have lost one orbiting electron) and multiply ionized heavier elements, such as oxygen, nitrogen, and silicon (the latter lines are not shown in the figure). These strong lines are not seen in the spectra of cooler stars because only very hot stars can excite and ionize such tightly bound atoms.
- In contrast, the hydrogen absorption lines in the spectra of very hot stars are relatively *weak*. The reason is not a lack of hydrogen, which is by far the most abundant element in all stars. Rather, at these high temperatures, much of the hydrogen is ionized, so there are few intact hydrogen atoms to produce strong spectral lines.
- Hydrogen lines are strongest in stars having intermediate surface temperatures of around 10,000 K. This temperature is just right for electrons to move frequently between hydrogen's second and higher orbitals, producing the characteristic visible hydrogen spectrum. ∞ *(Sec. 2.6)*

TABLE 10.1 Stellar Colors and Temperatures

Surface Temperature (K)	Color	Familiar Examples
30,000	electric blue	Mintaka (δ Orionis)
20,000	blue	Rigel
10,000	white	Vega, Sirius
7,000	yellow-white	Canopus
6,000	yellow	Sun, Alpha Centauri
4,000	orange	Arcturus, Aldebaran
3,000	red	Betelgeuse, Barnard's Star

- Hydrogen lines are again weak in stars with surface temperatures below about 4000 K because the temperature is too low to boost many electrons out of the ground state. ∞ *(Sec. 2.6)* The most intense spectral lines in these stars are due to weakly excited heavy atoms and from some molecules, as noted at the bottom of Figure 10.9.

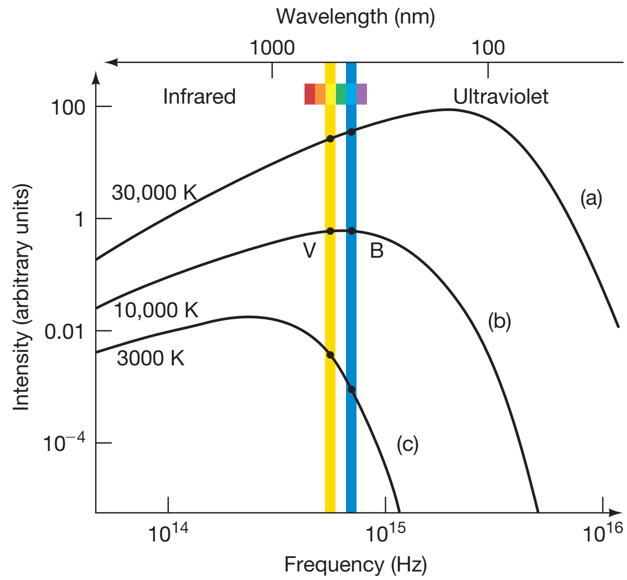
Stellar spectra are the source of all the detailed information we have on stellar composition, and they do reveal significant composition differences among stars, particularly in the abundances of carbon, nitrogen, oxygen, and heavier elements. However, as we have just seen, these differences are *not* the primary reason for the different spectra observed. Instead, the main determinant of a star's spectral appearance is its temperature, and stellar spectroscopy is a powerful and precise tool for measuring this important stellar property.

Spectral Classification

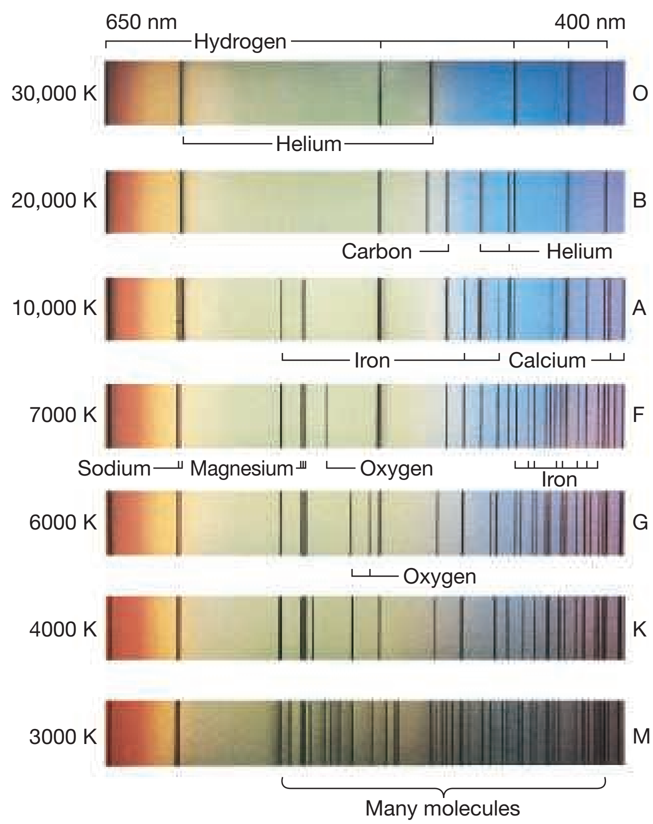
Astronomers obtained stellar spectra like those shown in Figure 10.9 for numerous stars around the start of the 20th century, as observatories around the world amassed stellar data from both hemispheres of the sky. Between 1880 and 1920, researchers correctly identified many of the observed spectral lines by comparing them with lines obtained in the laboratory. However, modern atomic theory had not yet been developed, so the correct interpretation of the line strengths, as just described, was impossible at the time. Lacking full understanding of how atoms produce spectra, astronomers organized their data by classifying stars according to their most prominent spectral features—especially their hydrogen-line intensities. They adopted an alphabetic scheme in which A stars, with the strongest hydrogen lines, were thought to have more hydrogen than did B stars, and so on. The classification extended as far as the letter P.

In the 1920s scientists began to understand the intricacies of atomic structure and the causes of spectral lines. Astronomers realized that stars could be more meaningfully classified according to surface temperature. But instead of adopting an entirely new scheme, they chose to shuffle the existing alphabetical categories—based on the strength of hydrogen lines—into a new sequence based on temperature. In order of decreasing temperature, the letters now run O, B, A, F, G, K, M. (The other letter classes have been dropped.) These stellar designations are called **spectral classes** (or *spectral types*). Use the mnemonic "**O**h, **B**e **A** **F**ine **G**uy/**G**irl, **K**iss **M**e" to remember them in the correct order.

Astronomers further divide each lettered spectral class into 10 subdivisions, numbered 0 to 9. The lower the number, the hotter the star. For example, our Sun is classified as a G2 star (a little cooler than G1 and a little hotter than G3), Vega is A0, Barnard's star is M5, Betelgeuse is M2, and so on. Table 10.2 lists the main properties of each stellar spectral class for the stars presented in Table 10.1.



▲ **FIGURE 10.8 Blackbody Curves Star** (a) is very hot—30,000 K—so its B (blue) intensity is greater than its V (visual) intensity. Star (b) has roughly equal B and V readings and so appears white. Its temperature is about 10,000 K. Star (c) is red; its V intensity greatly exceeds the B value, and its temperature is 3000 K.



▲ **FIGURE 10.9 Stellar Spectra** Comparison of spectra observed for seven different stars having a range of surface temperatures. The spectra of the hottest stars, at the top, show lines of helium and multiply ionized heavy elements. In the coolest stars, at the bottom, helium lines are absent, but lines of neutral atoms and molecules are plentiful. At intermediate temperatures, hydrogen lines are strongest.

TABLE 10.2 Spectral Classes

Spectral Class	Temperature (K)	Prominent Absorption Lines	Familiar Examples
O	30,000	Ionized helium strong; multiply ionized heavy elements; hydrogen faint	Mintaka (O9)
B	20,000	Neutral helium moderate; singly ionized heavy elements; hydrogen moderate	Rigel (B8)
A	10,000	Neutral helium very faint; singly ionized heavy elements; hydrogen strong	Vega (A0), Sirius (A1)
F	7000	Singly ionized heavy elements; neutral metals; hydrogen moderate	Canopus (F0)
G	6000	Singly ionized heavy elements; neutral metals; hydrogen relatively faint	Sun (G2), Alpha Centauri (G2)
K	4000	Singly ionized heavy elements; neutral metals strong; hydrogen faint	Arcturus (K2), Aldebaran (K5)
M	3000	Neutral atoms strong; molecules moderate; hydrogen very faint	Betelgeuse (M2)
			Barnard's Star (M5)

PROCESS OF SCIENCE CHECK

The spectral classification scheme developed by astronomers around the start of the 20th century was based on assumptions now known to be incorrect. Why then did it prove to be so useful?

CONCEPT CHECK

Why does a star's spectrum depend on its temperature?

We should not underestimate the importance of the early work in classifying stellar spectra. Even though the original classification was based on erroneous assumptions, the painstaking accumulation of large quantities of accurate and well-categorized data paved the way for rapid improvements in understanding once a theory came along that explained the observations.

10.4 Stellar Sizes

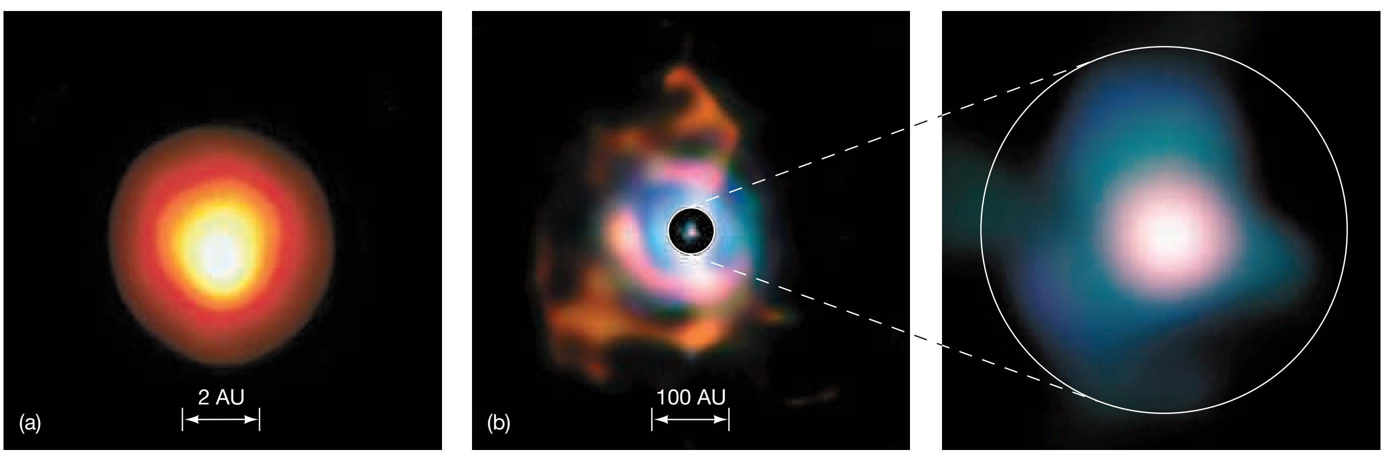
Direct and Indirect Measurements

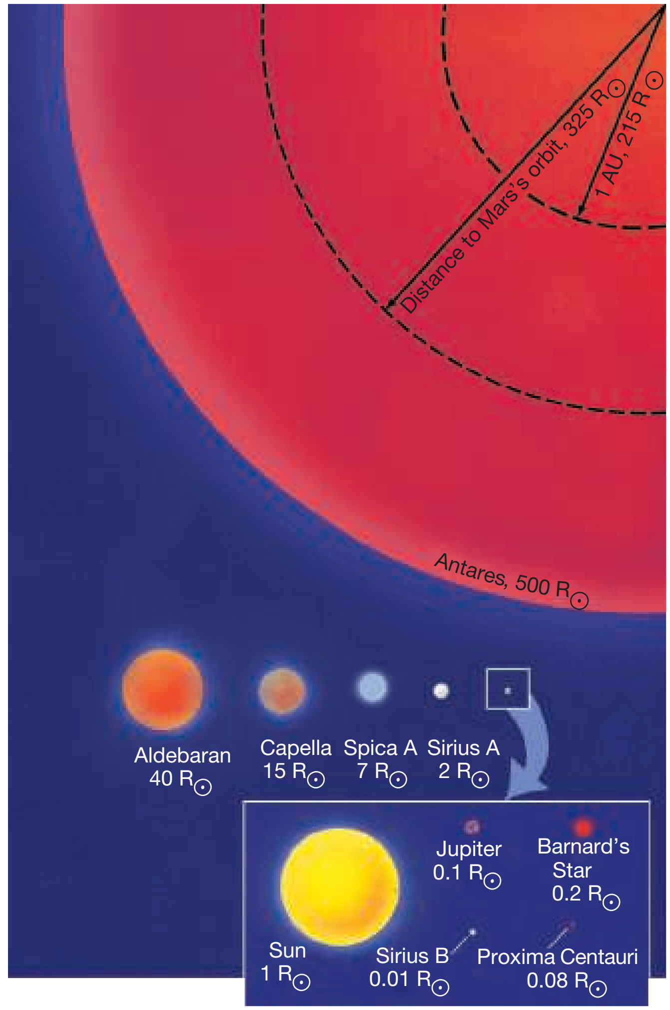
Virtually all stars are unresolvable points of light in the sky, even when viewed through the largest telescopes. Still, a few are big enough, bright enough, and close enough to allow us to measure their sizes directly. In some cases, the results are even detailed enough to allow us to distinguish a few surface features (Figure 10.10). By measuring a star's angular size and knowing its distance from the Sun, astronomers can determine its radius using simple geometry. ∞ *(More Precisely 4-1)* The sizes of a few dozen stars have been measured in this way.

Most stars are too distant or too small for such direct measurements to be possible. Their sizes must be inferred by more indirect means, using the radiation laws. ∞ *(Sec. 2.4)* According to the Stefan-Boltzmann law, the rate at which a star emits energy into space—the star's luminosity—is proportional to the fourth power of the star's surface temperature. ∞ *(More Precisely 2-2)* However, the luminosity also depends on the star's surface area, because large bodies radiate more energy than do small bodies having the same surface temperature. Because the surface area of a star is proportional to the square of its radius, we can say

$$\text{luminosity} \propto \text{radius}^2 \times \text{temperature}^4.$$

▼ **FIGURE 10.10 Betelgeuse** (a) The supergiant star Betelgeuse is large enough and close enough for astronomers to resolve its size directly. Betelgeuse is roughly 600 times the size of the Sun, making its photosphere comparable to Jupiter's orbit. This false-color ultraviolet view was taken by the *Hubble Space Telescope*. Hints of surface features, thought to be storms similar to (but much larger than) those found on the Sun can be seen. (b) These infrared views of Betelgeuse from the Very Large Telescope in Chile show the swollen star puffing out huge plumes of gas into its surroundings. *(NASA/ESA/ESO)*





▶ **FIGURE 10.11 Stellar Sizes** Shown here are the greatly varying sizes of several well-known stars. Only part of the red-giant star Antares can be shown on this scale, and the supergiant Betelgeuse would fill the entire page. (Here and in other figures, the symbol "☉" stands for the Sun, so the symbol "$R_\odot$" here means "solar radius.")

This **radius–luminosity–temperature relationship** is important because it demonstrates that knowledge of a star's luminosity and temperature can yield an estimate of its radius—an *indirect* determination of stellar size.

Giants and Dwarfs

Let's consider some examples to clarify these ideas. *More Precisely 10-2* (p. 294) presents more detail on the calculations involved. The star known as Aldebaran (the orange-red "eye of the bull" in the constellation Taurus) has a surface temperature of about 4000 K and a luminosity of 1.3×10^{29} W. Thus, its surface temperature is 0.7 times, and its luminosity about 330 times, the corresponding quantities for our Sun. The radius–luminosity–temperature relationship then implies that the star's radius is almost 40 times the solar value. If our Sun were that large, its photosphere would extend halfway to the orbit of Mercury and, seen from Earth, would cover more than 20° on the sky.

A star as large as Aldebaran is known as a *giant*. More precisely, **giants** are stars having radii between 10 and 100 times that of the Sun. Since any 4000-K object is reddish in color, Aldebaran is known as a **red giant.** Even larger stars, ranging up to 1000 solar radii in size, are known as **supergiants.** Betelgeuse is a prime example of a **red supergiant.**

Now consider Sirius B—a faint companion to Sirius A, the brightest star in the night sky. Sirius B's surface temperature is roughly 24,000 K, four times that of the Sun. Its luminosity is 10^{25} W, about 0.025 times the solar value. The radius–luminosity–temperature relationship then gives us a radius of 0.01 times the solar radius—roughly the size of Earth. Sirius B is much hotter but smaller and fainter than our Sun. Such a star is known as a *dwarf*. In astronomical parlance, the term **dwarf** refers to any star of radius comparable to or smaller than the radius of the Sun (including the Sun itself). Because any 24,000 K object glows bluish-white, Sirius B is an example of a **white dwarf.**

Stellar radii range from less than 0.01 to more than 100 times the radius of the Sun. Figure 10.11 illustrates the sizes of a few well-known stars.

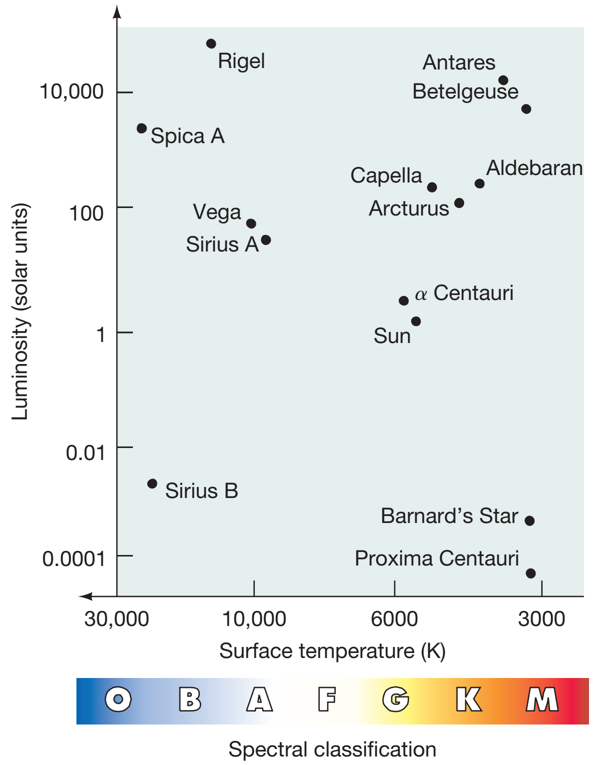
CONCEPT CHECK

Can we measure the radius of a star without knowing its distance?

10.5 The Hertzsprung–Russell Diagram

Figure 10.12 plots luminosity versus temperature for a few well-known stars. A figure of this sort is called a *Hertzsprung–Russell diagram,* or **H–R diagram,** after Danish astronomer Ejnar Hertzsprung and U.S. astronomer Henry Norris Russell, who independently pioneered the use of such plots in the 1920s. The vertical luminosity scale, expressed in units of solar luminosity (3.9×10^{26} W), extends over a large range, from 10^{-4} to 10^4. The Sun appears right in the middle of the luminosity range, at a luminosity of 1. Surface temperature is plotted on the horizontal axis, although in the unconventional sense of temperature increasing to the *left,* so that the spectral sequence O, B, A, . . . reads left to right.

MA SELF-GUIDED TUTORIAL
Hertzsprung–Russell Diagram



◀ **FIGURE 10.12 H–R Diagram of Well-Known Stars** A plot of luminosity against surface temperature (or spectral class) is a useful way to compare stars. Plotted here are the data for some stars mentioned earlier in the text, including the Sun, which has a luminosity of 1 solar unit and a temperature of 5800 K—a G-type star. The B-type star Rigel, at top left, has a temperature of about 11,000 K and a luminosity more than 10,000 times that of the Sun. The M-type star Proxima Centauri, at bottom right, has a temperature of about 3000 K and a luminosity less than 1/10,000 that of the Sun.

The Main Sequence

The few stars plotted in Figure 10.12 give little indication of any particular connection between stellar properties. However, as Hertzsprung and Russell plotted more and more stellar temperatures and luminosities, they found that a relationship does in fact exist. Stars are *not* uniformly scattered across the H–R diagram. Instead, most are confined to a fairly well-defined band stretching diagonally from top left (high-temperature, high-luminosity) to bottom right (low-temperature, low-luminosity). In other words, cool stars tend to be faint (less luminous) and hot stars tend to be bright (more luminous). This band of stars spanning the H–R diagram is known as the **main sequence.** Figure 10.13 is an H–R diagram for stars lying within 5 pc of the Sun. Note that most stars in the solar neighborhood lie on the main sequence.

A useful analogy involves human beings. Our height and weight are also correlated along a "main sequence." That is, as shown near Figure 10.13, the majority of the human population falls within a diagonal area (bounded by the shaded area). This is true since tall people usually weigh more than shorter ones. Some exceptions—including dwarfs and basketball players—lie outside this well-defined range.

The surface temperatures of main-sequence stars range from about 3000 K (spectral class M) to more than 30,000 K (spectral class O). This temperature range is relatively small—only a factor of 10. In contrast, the observed range in luminosities is very large, covering eight orders of magnitude (that is, a factor of 100 million), from 10^{-4} to 10^{4} the luminosity of the Sun.

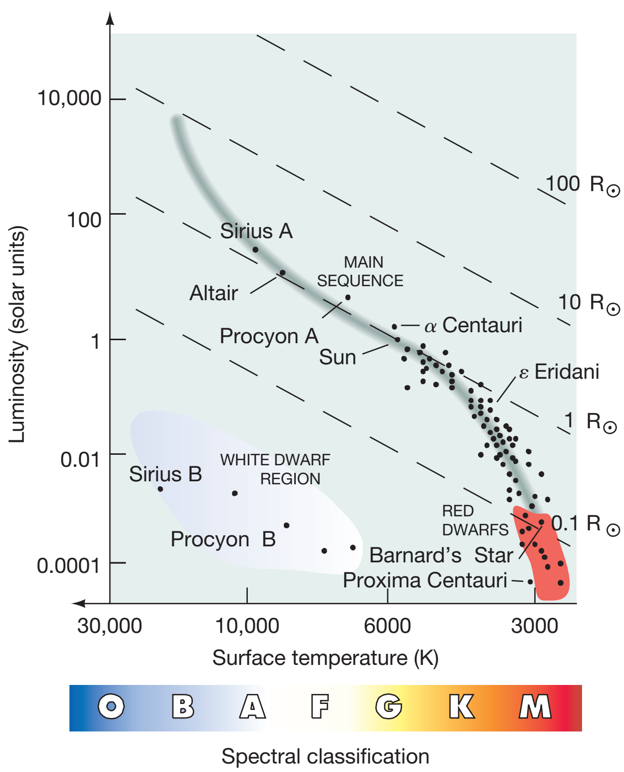
Using the radius–luminosity–temperature relationship (Section 10.4), astronomers find that stellar radii also vary along the main sequence. The faint, red M-type stars in the bottom right of the H–R diagram are only about 1/10 the size of the Sun, whereas the bright, blue O-type stars in the upper left are about 10 times larger than the Sun. The dashed lines in Figure 10.13 represent constant stellar radius, meaning that any star lying on a given line has the same radius, regardless of its luminosity or temperature. Along a constant-radius line, the radius–luminosity– temperature relationship implies

$$\text{luminosity} \propto \text{temperature}^4.$$

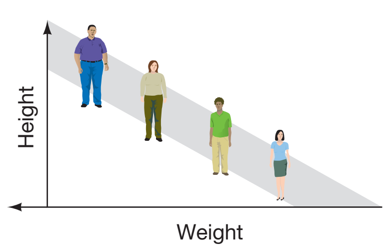
By including such lines on our H–R diagrams, we can indicate stellar temperatures, luminosities, and radii on a single plot.

At the top end of the main sequence, the stars are large, hot, and very luminous. Because of their size and color, they are referred to as **blue giants.** The very largest are called **blue supergiants.** At the other end, stars are small, cool, and faint. They are known as **red dwarfs.** Our Sun lies right in the middle.

Figure 10.14 shows an H–R diagram for a different group of stars—the 100 stars of known distance having the greatest apparent brightness, as seen from



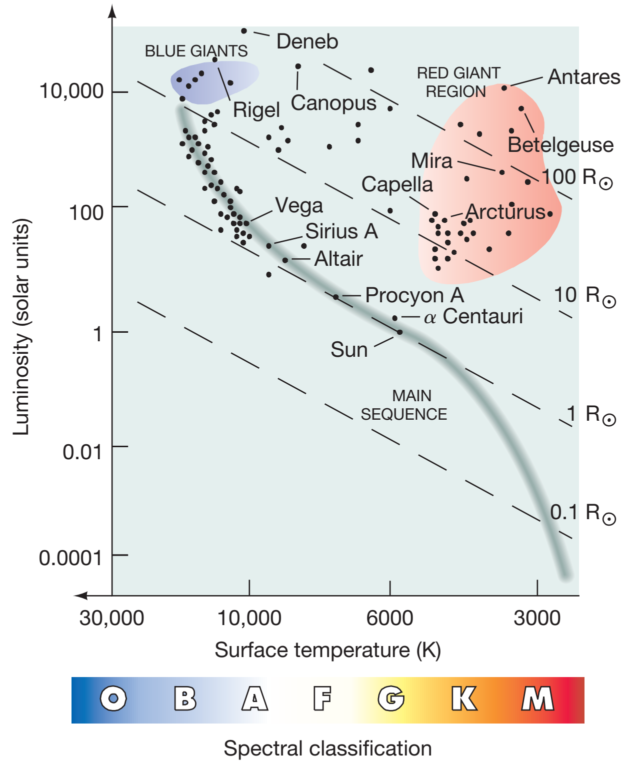
Analogous to an H–R diagram, people's height and weight fall along a "main sequence."



◀ **FIGURE 10.13 H–R Diagram of Nearby Stars INTERACTIVE** Most stars have properties within the long, thin shaded region of the H–R diagram known as the main sequence. The points plotted here are for stars lying within about 5 pc of the Sun. Each dashed diagonal line corresponds to a constant stellar radius. (Recall that the symbol "R☉" means "solar radius.")

Earth. Notice that here there are many more stars at the upper end of the main sequence than at the lower end. The reason for this excess of blue giants is simple—we can see very luminous stars a long way off. The stars shown in Figure 10.14 are scattered through a much greater volume of space than those shown in Figure 10.13, and the Figure 10.14 sample is heavily biased toward the most luminous objects. In fact, of the 20 brightest stars in the sky, only 6 lie within 10 pc of us. The rest are visible, despite their great distances, because of their high luminosities.

If very luminous blue giants are overrepresented in Figure 10.14, low-luminosity red dwarfs are surely underrepresented. In fact, no dwarfs appear on this diagram. This absence is not surprising, because low-luminosity stars are difficult to observe from Earth. In the 1970s, astronomers began to realize that they had greatly underestimated the number of red dwarfs in our Galaxy. As hinted at by the H–R diagram in Figure 10.13, which shows an unbiased sample of stars in the solar neighborhood, red dwarfs are actually the most common type of star in the sky. They probably account for upward of 80 percent of all stars in the universe. In contrast, O- and B-type supergiants are extremely rare—only about one star in 10,000 falls into this category.



▲ **FIGURE 10.14 H–R Diagram of Brightest Stars**
INTERACTIVE An H–R diagram for the 100 brightest stars in the sky is biased in favor of the most luminous stars—which appear toward the upper left—because we can see them more easily than we can the faintest stars. (Compare with Figure 10.13, which shows only the closest stars.)

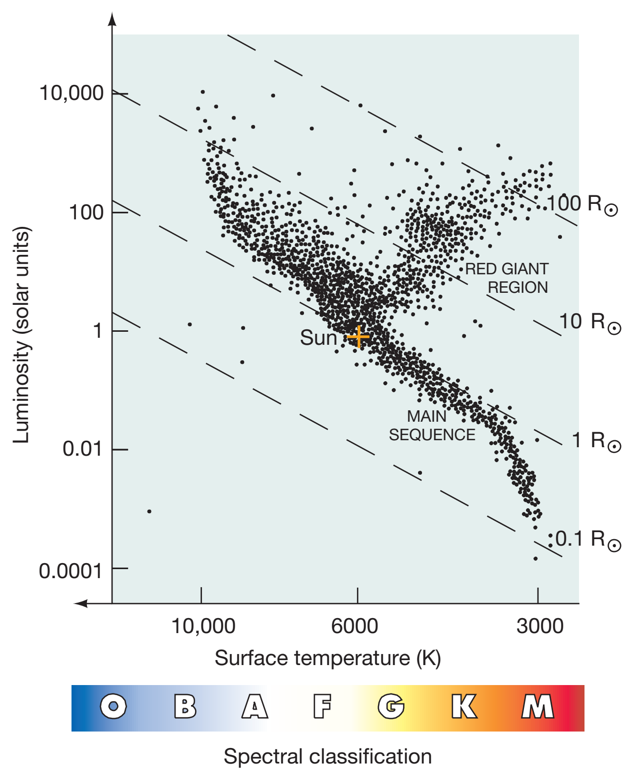
The White-Dwarf and Red-Giant Regions

Some of the points plotted in Figures 10.12–10.14 clearly do not lie on the main sequence. One such point in Figure 10.12 represents Sirius B, the white dwarf we met in Section 10.4 (see *More Precisely 10-2*). Its surface temperature (24,000 K) is about four times greater than that of the Sun, but its luminosity is hundreds of times less than the solar value. A few more such faint bluish-white stars can be seen in the bottom left-hand corner of Figure 10.13, in the **white-dwarf region**.

Also shown in Figure 10.12 is Aldebaran, with a surface temperature (4000 K) about two-thirds that of the Sun, but with a luminosity more than 300 times greater than the Sun's. Another point represents Betelgeuse, the ninth brightest star in the sky, a little cooler than Aldebaran, but nearly 100 times more luminous. The upper right-hand corner of the H–R diagram (marked on Figure 10.14), where these stars are found, is called the **red-giant region.** No red giants are found within 5 pc of the Sun (Figure 10.13), but many of the brightest stars seen in the sky are in fact red giants (Figure 10.14). Red giants are relatively rare, but they are so bright that they are visible at very great distances. They form a third distinct class of stars in the H–R diagram, very different in their properties from both main-sequence stars and white dwarfs.

The *Hipparcos* mission (Section 10.1), in addition to determining hundreds of thousands of stellar parallaxes with unprecedented accuracy, also measured the colors and luminosities of more than 2 million stars. Figure 10.15 shows an H–R diagram based on a tiny portion of the enormous *Hipparcos* dataset. The main sequence and red giant regions are clearly evident. Few white dwarfs appear, however, because the telescope was limited to observations of relatively bright objects—brighter than apparent magnitude 12. Almost no white dwarfs lie close enough to Earth that their magnitudes fall below this limit.

About 90 percent of all stars in our solar neighborhood, and presumably a similar percentage elsewhere in the universe, are main-sequence stars. About 9 percent of stars are white dwarfs, and 1 percent are red giants.



▶ **FIGURE10.15** *Hipparcos* **H–R Diagram** This simplified version of the most complete H–R diagram ever compiled represents more than 20,000 data points, as measured by the European *Hipparcos* spacecraft for stars within a few hundred parsecs of the Sun.

10.2 MORE PRECISELY

Estimating Stellar Radii

We can combine the Stefan-Boltzmann law $F = \sigma T^4$ with the formula for the area of a sphere, $A = 4\pi R^2$, to obtain the relationship between radius (R), luminosity (L), and temperature (T) described in the text ∞ *(More Precisely 2-2)*:

$$L = FA = 4\pi\sigma R^2 T^4$$

or

$$\text{luminosity} \propto \text{radius}^2 \times \text{temperature}^4.$$

If we adopt convenient solar units, in which L is measured in solar luminosities (3.9×10^{26} W), R is measured in solar radii (696,000 km), and T in units of the solar temperature (5800 K), we can remove the constant $4\pi\sigma$ and write this equation as

$$L(\text{in solar luminosities}) = R^2 \text{ (in solar radii)} \times T^4 (\text{in units of 5800 } K).$$

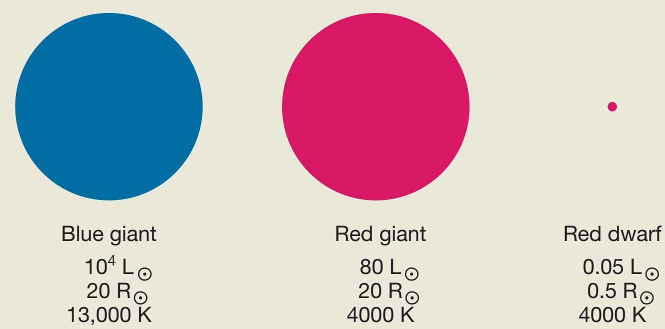
As illustrated in the accompanying figure, both the radius and the temperature are important in determining the star's luminosity.

To compute the radius of a star from its luminosity and temperature, we rearrange this equation to read (in the same units)

$$R = \frac{\sqrt{L}}{T^2}.$$

This simple application of the radiation laws is the basis for almost every estimate of stellar size made in this book.

Let's take as examples the two stars discussed in the text. The red giant star Aldebaran has luminosity $L = 330$ units and temperature $T = 4000/5800 = 0.69$ unit. According to the foregoing equation for R, its radius is therefore $\sqrt{330/0.69^2} = 18/0.48 = 39$ times the radius of the Sun. At the opposite extreme, the white dwarf Sirius B has $L = 0.025$ and $T = 4.7$, so its radius is $\sqrt{10.025}/4.7^2 = 0.16/22 \approx 0.007$ is solar radii.



10.6 Extending the Cosmic Distance Scale

We have already discussed the connections between luminosity, apparent brightness, and distance. Knowledge of a star's apparent brightness and its distance allows us to determine its luminosity using the inverse-square law. But we can also turn the problem around. If we somehow knew a star's luminosity and then measured its apparent brightness, the inverse-square law would tell us its distance from the Sun.

CONCEPT CHECK

Only a tiny fraction of all stars are giants. Why, then, do giants account for so many of the stars visible to the naked eye in the night sky?

Spectroscopic Parallax

ANIMATION/VIDEO
White Dwarfs in Globular Cluster
MA

Most of us have a rough idea of the approximate intrinsic brightness (that is, the luminosity) of a typical traffic signal. Suppose you are driving down an unfamiliar street and see a red traffic light in the distance. Your knowledge of the light's luminosity enables you immediately to make a mental estimate of its distance. A light that appears relatively dim (low apparent brightness) must be quite distant (assuming it's not just dirty). A bright one must be relatively close. Thus, *measurement of the apparent brightness of a light source, combined with some knowledge of its luminosity, can yield an estimate of its distance.*

For a star the trick is to find an independent measure of luminosity without knowing the distance. The H–R diagram can provide just that. For example, suppose we observe a star and determine its apparent magnitude to be 10. By itself, that doesn't tell us much—the star could either be faint and close, or bright and distant (Figure 10.5). But suppose we have some additional information: The star lies on the main sequence and has spectral type A0. Then we can read the star's luminosity off a graph such as Figure 10.13 or Figure 10.14. A main-sequence A0 star has a luminosity of approximately 100 solar units. According to *More Precisely 10-1*, this corresponds to an absolute magnitude of 0 and hence to a distance of 1000 pc.

This process of using stellar spectra to infer distances is called **spectroscopic parallax.** The key steps are as follows:

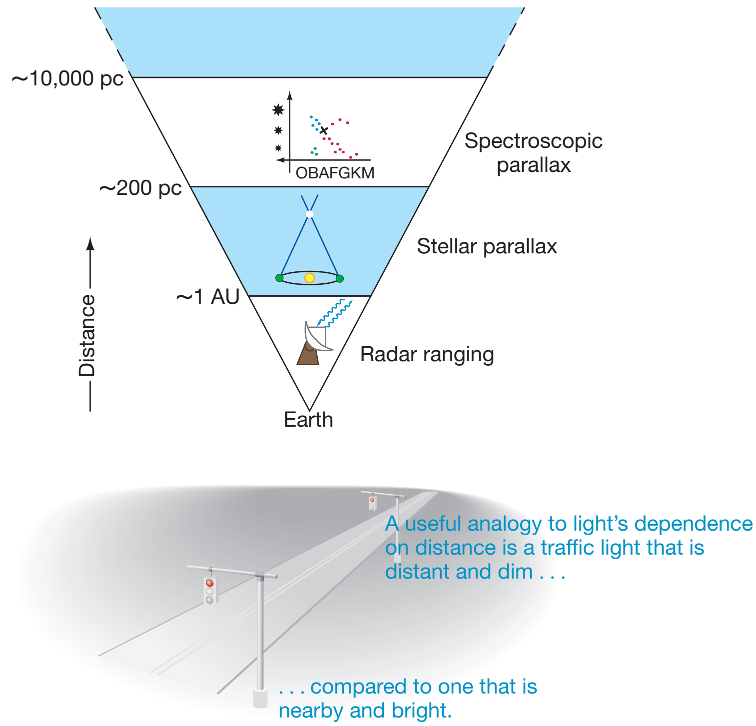
1. measure the star's apparent brightness and spectral type *without* knowing how far away it is;
2. use the spectral type to estimate the star's luminosity, assuming that it lies on the main sequence; and
3. finally, apply the inverse-square law to determine the distance to the star.

Note that despite its name, the method has nothing in common with stellar (geometric) parallax other than its use as a means of determining stellar distances. The main sequence allows us to make a connection between an easily measured quantity (spectral type) and the star's luminosity, which would otherwise be unknown. As we will see in upcoming chapters, this essential logic (with a variety of different techniques replacing step 2) is used again and again as a means of distance measurement in astronomy. In practice, the "fuzziness" of the main sequence translates into a small (10 − 20 percent) uncertainty in the distance, but the basic idea remains valid.

In Chapter 1 we introduced the first rung on a ladder of distance-measurement techniques that will ultimately carry us to the edge of the observable universe. That rung is radar ranging on the inner planets. ∞ *(Sec.1.3)* It establishes the scale of the solar system and defines the astronomical unit. At the beginning of this chapter we discussed a second rung on the cosmic distance ladder—stellar parallax—which is based on the first, since Earth's orbit is the baseline. Now, having used the first two rungs to determine the distances and other physical properties of many nearby stars, we use that knowledge to construct the third rung—spectroscopic parallax. Figure 10.16 illustrates schematically how this third rung builds on the first two and expands our cosmic field of view still deeper into space.

Spectroscopic parallax can be used to determine stellar distances out to several thousand parsecs. Beyond that, spectra and colors of individual stars are difficult to obtain. Note that, in using this method, we are assuming (without proof) that distant stars are basically similar to those nearby—in particular, that main-sequence stars *fall on the same main sequence.* Only by making this assumption can we use spectroscopic parallax to expand the boundaries of our distance-measurement techniques.

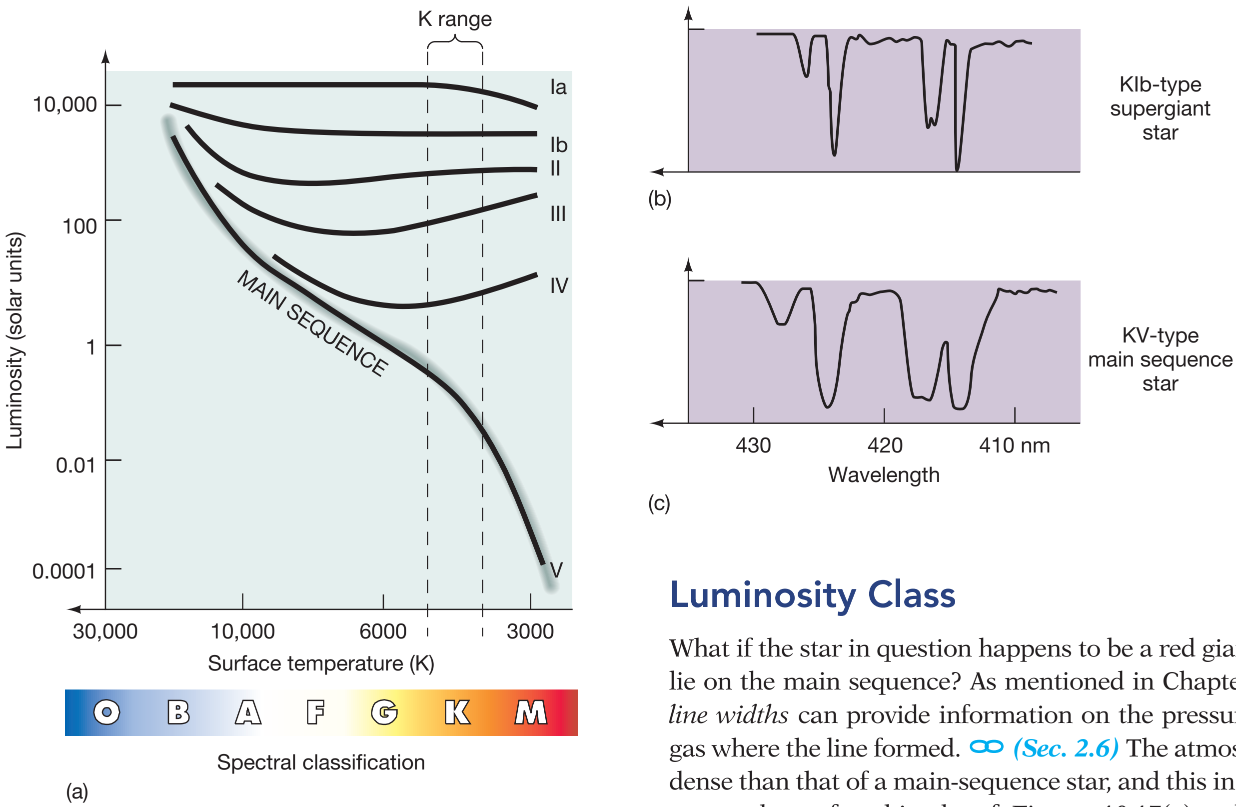
Each rung in the distance ladder is calibrated using data from the lower rungs, so changes made at any level will affect measurements made on *all* larger scales. As a result, the impact of the enormous dataset of high-quality observations returned by the *Hipparcos* mission (Section 10.1) extends far beyond the volume of space actually surveyed by the satellite. By recalibrating the local foundations of the cosmic distance scale, *Hipparcos* has revised estimates of distances on *all* scales—up to and including the scale of the universe itself. All distances quoted throughout this text reflect updated values based on *Hipparcos* data.



▲ **FIGURE 10.16 Stellar Distances INTERACTIVE** Knowledge of a star's luminosity and apparent brightness can yield an estimate of its distance. Astronomers use this third rung on the distance ladder, called spectroscopic parallax, to measure distances as far out as individual stars can be clearly discerned—several thousand parsecs.

CONCEPT CHECK

Suppose astronomers discover that due to a calibration error all distances measured by geometric parallax are 10 percent larger than currently thought. What effect would this have on the "standard" main sequence used in spectroscopic parallax?



◀ **FIGURE 10.17 Luminosity Classes** (a) Approximate locations of the standard stellar luminosity classes in the H–R diagram. The widths of absorption lines also provide information on the density of a star's atmosphere. The denser atmosphere of a main-sequence K-type star has broader lines (c) than a giant star of the same spectral class (b).

PROCESS OF SCIENCE CHECK

What assumptions are we making when we apply spectroscopic parallax to measure the distance to a star?

TABLE 10.3 Stellar Luminosity Classes

Class	Description
Ia	bright supergiants
Ib	supergiants
II	bright giants
III	giants
IV	subgiants
V	main-sequence stars/dwarfs

Luminosity Class

What if the star in question happens to be a red giant or a white dwarf and does not lie on the main sequence? As mentioned in Chapter 2, detailed analysis of spectral *line widths* can provide information on the pressure, and hence the density, of the gas where the line formed. ∞ *(Sec. 2.6)* The atmosphere of a red giant is much less dense than that of a main-sequence star, and this in turn is much less dense than the atmo-sphere of a white dwarf. Figures 10.17(a) and (b) illustrate the differences between the spectra of a main-sequence star and a red giant of the same spectral type.

Over the years, astronomers have developed a system for classifying stars according to the widths of their spectral lines. Because line width depends on pressure in the stellar photosphere, and because this pressure in turn is well correlated with luminosity, this stellar property is known as **luminosity class.** The standard luminosity classes are listed in Table 10.3 and shown on the H–R diagram in Figure 10.17(c). By determining a star's luminosity class, astronomers can usually tell with a high degree of confidence what sort of object it is and the full specification of a star's spectral properties includes its luminosity class. For example, the Sun, a G2 main-sequence star, is of class G2V, the B8 blue supergiant Rigel is B8Ia, the red dwarf Barnard's star is M5V, the red supergiant Betelgeuse is M2Ia, and so on.

Consider, for example, a K2-type star (Table 10.4) with a surface temperature of around 4500 K. If the widths of the star's spectral lines tell us that it lies on the main sequence (i.e., it is a K2V star), then its luminosity is about 0.3 times the solar value. If the lines are narrower than those normally found in main-sequence stars, the star may be recognized as a K2III giant, with a luminosity 100 times that of the Sun (Figure 10.17c). If the lines are very narrow, the star might instead be classified as a K2Ib supergiant, brighter by a further factor of 40, at 4000 solar luminosities. In each case, knowledge of luminosity classes allows astronomers to identify the object and make a useful estimate of its luminosity and hence its distance.

TABLE 10.4 Variation in Stellar Properties within a Spectral Class

Surface Temperature (K)	Luminosity (solar luminosities)	Radius (solar radii)	Object	Example
4900	0.3	0.8	K2V main-sequence star	ε Eridani
4500	110	21	K2III red giant	Arcturus
4300	4000	140	K2Ib red supergiant	ε Pegasi

10.7 Stellar Masses

As with all other astronomical objects, we measure a star's mass by observing its gravitational influence on some nearby body—another star, perhaps, or a planet. If we know the distance between the two bodies, we can use Newton's laws to calculate their masses. ∞ *(Sec. 1.4)*

MA SELF-GUIDED TUTORIAL
Binary Stars–Radial Velocity Curves

MA SELF-GUIDED TUTORIAL
Eclipsing Binary Stars–Light Curves

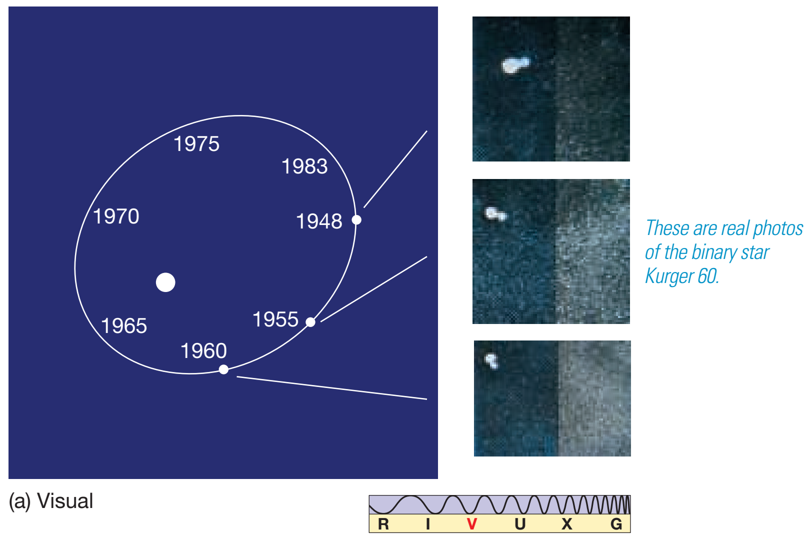
Binary Stars

Most stars are members of *multiple-star systems*—groups of two or more stars in orbit around one another. The majority form **binary-star systems** (or simply *binaries*), which consist of two stars in orbit about their common center of mass, held together by their mutual gravitational attraction. (The Sun is not part of a multiple star system; if it has anything at all uncommon about it, it is this lack of stellar companions.)

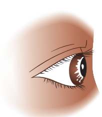
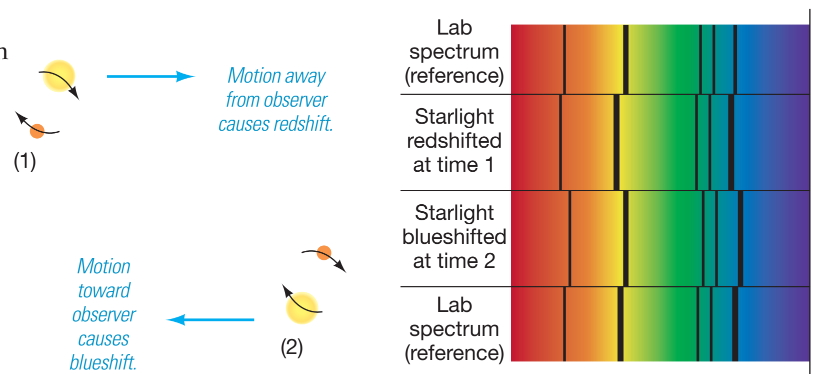
Astronomers classify binaries according to their appearance from Earth and the ease with which they can be observed. **Visual binaries** have widely separated components bright enough to be observed and monitored separately (Figure 10.18a). The more common **spectroscopic binaries** are too distant from us to be resolved into two distinct stars, but they can be indirectly perceived by monitoring the back-and-forth Doppler shifts of their spectral lines as the stars orbit one another and their line-of-sight velocities vary periodically. ∞ *(Sec. 2.7)*

In a *double-line* spectroscopic binary, two distinct sets of spectral lines—one for each component star—shift back and forth as the stars move. The periodic shifts of the lines tell us that the objects emitting them are in orbit. In the more common *single-line* systems (Figure 10.18b), one star is too faint for its spectrum to be distinguished, so we see only one set of lines shifting back and forth. This shifting means that the detected star must be in orbit around another star, even though the companion cannot be observed directly. (If this idea sounds familiar, it should—all the extrasolar planetary systems discovered to date are extreme examples of single-line spectroscopic binaries.) ∞ *(Sec. 4.4)*

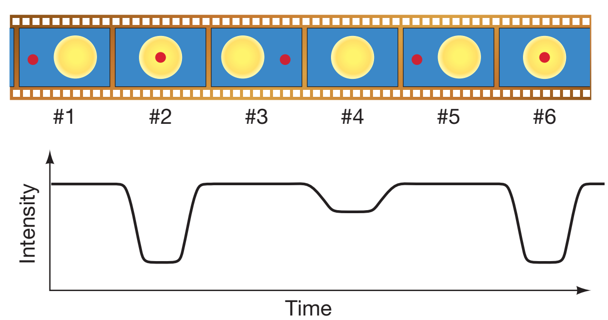
In the much rarer **eclipsing binaries,** the orbital plane of the pair of stars is almost edge-on to our line of sight. In this situation, we observe a periodic decrease of starlight intensity as one member of the binary passes in front of the other (Figure 10.18c). By studying the variation of the light from an eclipsing binary system—called the binary's **light curve**—astronomers can derive detailed information not only about the stars' orbits and masses, but also about their radii.



(a) Visual

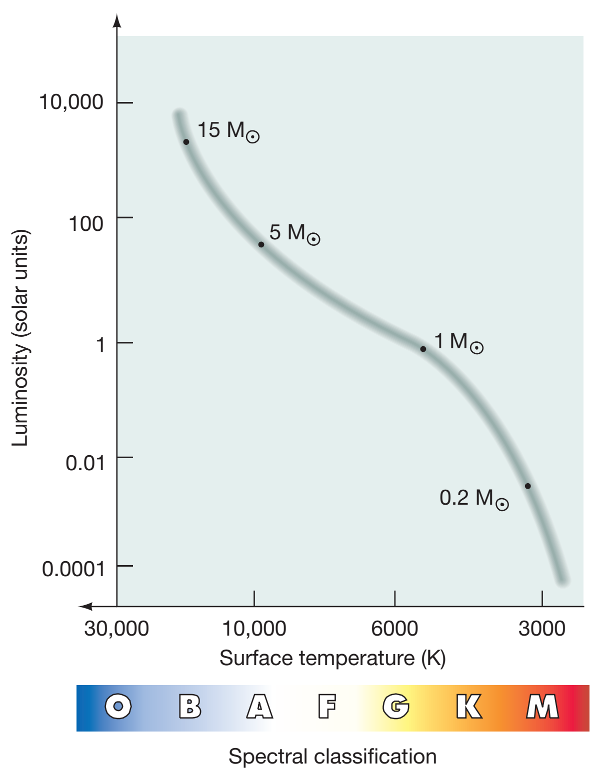
(b) Spectroscopic



(c) Eclipsing

▶ **FIGURE 10.18 Binary Stars** INTERACTIVE (a) The period and separation of a double-star system can be observed directly if each star is clearly seen. (b) Binary properties can be determined indirectly by measuring the periodic Doppler shift of one star relative to the other while moving in their orbits. This is a single-line system, in which only one spectrum (from the brighter component) is visible. (c) If two stars eclipse one another, additional information can be obtained by observing the periodic decrease in starlight as one star passes in front of the other. *(Harvard College Observatory)*

INTERACTIVE MA
Exploring the Light Curve of an Eclipsing Binary Star System



▲ **FIGURE 10.19 Stellar Masses** More than any other stellar property, mass determines a star's position on the main sequence. Low-mass stars are cool and faint; they lie at the bottom of the main sequence. Very massive stars are hot and bright; they lie at the top of the main sequence. (The symbol "M⊙" means "solar mass.")

Note that these categories are not mutually exclusive. For example, an eclipsing binary may also be (and in fact often is) a spectroscopic binary system.

Mass Determination

The period of a binary can be measured by observing the orbits of the component stars, the back-and-forth motion of the stellar spectral lines, or the dips in the light curve—whatever information is available. Observed binary periods span a broad range—from hours to centuries. How much additional information can be extracted depends on the type of binary involved.

If the distance to a *visual binary* is known, then the orbits of each component can be individually tracked and the masses of the components can be determined. *(Sec.1.4)*

For *spectroscopic binaries,* Doppler-shift measurements give us information only on the radial velocities of the component stars, and this limits the information we can obtain. Simply put, we cannot distinguish between a slow-moving binary seen edge-on and a fast-moving binary seen almost face-on (so that only a small component of the orbital motion is along the line of sight). For a double-line system, only lower limits on the individual masses can be obtained. For single-line systems, even less information is available, and only a rather complicated relation between the component masses (known as the mass function) can be derived.

If a spectroscopic binary also happens to be an eclipsing system, then the uncertainty in the orbital inclination is removed, as the binary is known to be edge-on (or very nearly so). In that case, both masses can be determined for a double-line binary. For a single-line system, the mass function is simplified to the point where the mass of the unseen component is known if the mass of the brighter component can be obtained by other means (for example, if it is recognized as a main-sequence star of a certain spectral class—see Figure 10.19).

Despite all these qualifications, individual component masses have been obtained for many nearby binary systems. A simple example is presented in *More Precisely 10-3*. Virtually all we know about the masses of stars is based on such observations.

Mass and Other Stellar Properties

Table 10.5 summarizes the various observational and theoretical techniques used to measure the stars, listing the quantities that are assumed known (usually as a result of the application of other techniques listed in the table), those that are measured, and the theory that is applied to turn the observations into the desired result. We end our introduction to the stars with a brief look at how mass is correlated with the other stellar properties discussed in this chapter.

Figure 10.19 is a schematic H–R diagram showing how stellar mass varies along the main sequence. There is a clear progression from low-mass red dwarfs to high-mass blue giants. With few exceptions, main-sequence stars range in mass from about 0.1 to 20 times the mass of the Sun. The hot O- and B-type stars are generally about 10 to 20 times more massive than our Sun. The coolest K- and M-type stars contain only a few tenths of a solar mass. The mass of a star at the time of its formation determines its location on the main sequence. Based on observations of stars within a few hundred light-years of the Sun, Figure 10.20 illustrates how the masses of main-sequence stars are distributed. Notice the huge fraction of low-mass stars, as well as the tiny fraction contributed by stars of more than a few solar masses.

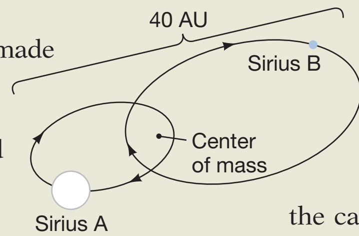
Figure 10.21 illustrates how the radii and luminosities of main-sequence stars depend on mass. The two plots are called the *mass–radius* (part a) and *mass–luminosity* (part b) relationships. Along the main sequence, both radius and luminosity increase with mass. The radius rises slightly more slowly than the

10.3 MORE PRECISELY

Measuring Stellar Masses in Binary Stars

As discussed in the text, most stars are members of binary systems—where two stars orbit one another, bound together by gravity. Here we describe how—in an idealized case where the relevant orbital parameters are known—we can use the observed orbital data, together with our knowledge of basic physics, to determine the masses of the component stars.

Consider the nearby visual binary system made up of the bright star Sirius A and its faint companion Sirius B, sketched in the accompanying figure. The binary's orbital period can be measured simply by watching the stars orbit one another, or alternatively by following the back-and-forth velocity wobbles of Sirius A due to its faint companion. It is almost exactly 50 years. The orbital semimajor axis can also be obtained by direct observation of the orbit, although in this case we must use some additional knowledge of Kepler's laws to correct for the binary's 46° inclination to the line of sight. *(Sec. 1.3)* It is 20 AU—an angular size of at a distance of 2.7 pc. *(Sec. 1.3)* Once we know these two key orbital parameters, we can use the modified version of Kepler's third law to calculate the sum of the masses of the two stars. The result is $20^3/50^2 = 3.2$ times the mass of the Sun. *(Sec. 1.4)*



Further study of the orbit allows us to determine the individual stellar masses. Doppler observations show that Sirius A moves at approximately half the speed of its companion relative to their center of mass. *(Secs. 1.4, 2.7)* This implies that Sirius A must have twice the mass of Sirius B. It then follows that the masses of Sirius A and Sirius B are 2.1 and 1.1 solar masses, respectively. Often the calculation of the masses of binary components is complicated by the fact that only partial information is available—we might only be able to see one star, or perhaps only spectroscopic velocity information is available (see Section 10.7). Nevertheless, this technique of combining elementary physical principles with detailed observations is how virtually every stellar mass quoted in this text has been determined.

mass, whereas luminosity increases much faster—more like the *fourth power* of the mass (indicated by the straight line in Figure 10.21b). For example, a 2-solar mass main-sequence star has a radius roughly twice that of the Sun and a luminosity of 16 (2^4) solar luminosities. A 0.2-solar mass main-sequence star has a radius of about 0.2 solar radii and a luminosity of 0.0016 (0.2^4) solar luminosities.

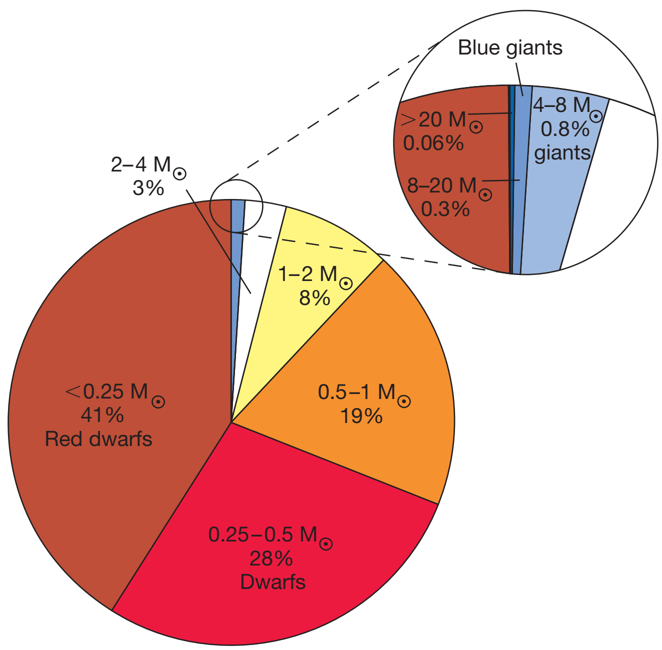
TABLE 10.5 Measuring the Stars

Stellar Property	Measurement Technique	"Known" Quantity	Measured Quantity	Theory Applied	Section
Distance	stellar parallax spectroscopic parallax	astronomical unit main sequence	parallactic angle spectral type apparent magnitude	elementary geometry inverse-square law	10.1 10.6
Radial velocity		speed of light atomic spectra	spectral lines	Doppler effect	10.1
Transverse velocity	astrometry	distance	proper motion	elementary geometry	10.1
Luminosity		distance main sequence	apparent magnitude spectral type color	inverse-square law	10.2 10.6
Temperature	photometry spectroscopy		spectral type	blackbody law atomic physics	10.3 10.3
Radius	direct indirect	distance	angular size luminosity temperature	elementary geometry radius–luminosity–temperature relationship	10.4 10.4
Composition	spectroscopy		spectrum	atomic physics	10.3
Mass	observations of binary stars	distance	binary period binary orbit orbital velocity	Newtonian gravity and dynamics	10.7

TABLE 10.6 Key Properties of Some Well-Known Main-Sequence Stars

Star	Spectral Type/ Luminosity Class[1]	Mass (solar masses)	Central Temperature (10^6 K)	Luminosity (solar luminosities)	Estimated Lifetime (millions of years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

*The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).



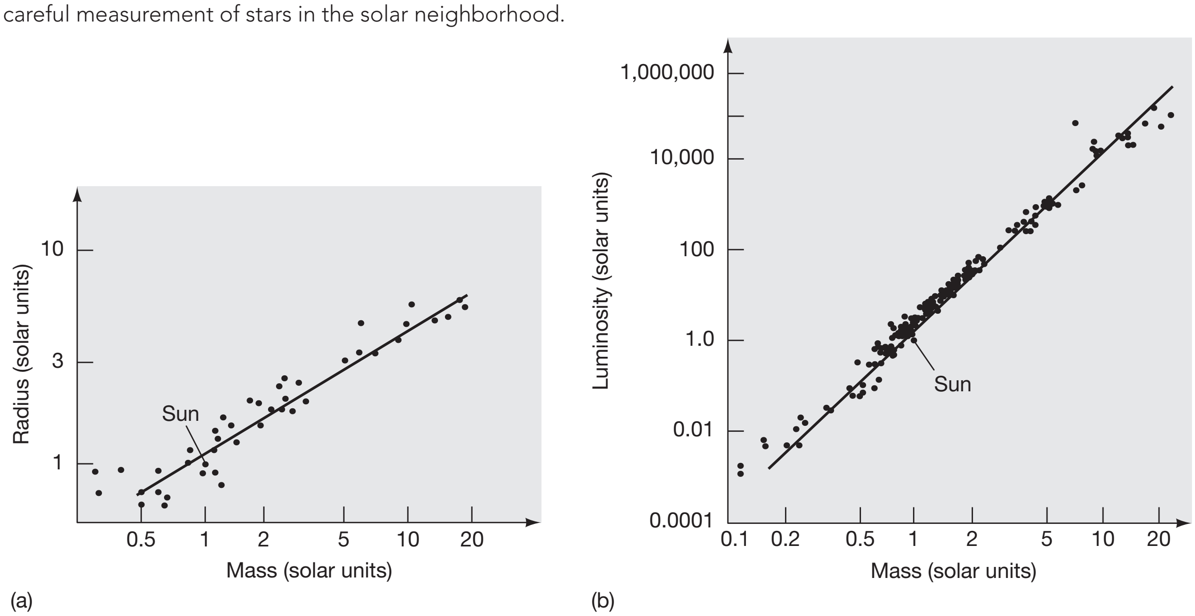
▲ **FIGURE 10.20 Stellar Mass Distribution** The distribution of masses of main-sequence stars, as determined from careful measurement of stars in the solar neighborhood.

Table 10.6 compares key properties of some well-known main-sequence stars, arranged in order of decreasing mass. Notice that the central temperature (obtained from mathematical models similar to those discussed in Chapter 9) differs relatively little from star to star, compared to the large spread in stellar luminosities. The final column in the table presents an estimate of each star's *lifetime*, obtained by dividing the amount of fuel available (that is, the star's mass) by the rate at which the fuel is consumed (the luminosity),

$$\text{stellar lifetime} \propto \frac{\text{stellar mass}}{\text{stellar luminosity}},$$

and noting that the lifetime of the Sun (see Chapter 12) is about 10 billion years.

Because luminosity increases so rapidly with mass, the most massive stars are by far the shortest lived. For example, according to the mass–luminosity relationship, the lifetime of a 10-solar mass O-type star is roughly $10/10^4$ = 1/1000 that of the Sun, or about 10 million years. We can be sure that all the O- and B-type stars we now observe are quite young—less than a few tens of millions of years old. Their nuclear reactions proceed so rapidly that their fuel is quickly depleted despite their large masses. At the opposite end of the main sequence, the low core density and temperature of an 0.1-solar mass M-type star



◀ **FIGURE 10.21 Stellar Radii and Luminosities** (a) Actual measurements of main-sequence stars show that radius increases almost in proportion to mass over much of the range (as indicated by the straight line drawn through the data). (b) Stellar luminosity increases roughly as the fourth power of the mass (indicated again by the straight line).

mean that its proton–proton reactions churn away much more sluggishly than in the Sun's core, leading to a very low luminosity and a correspondingly long lifetime. (*Sec. 9.5*) Many of the K- and M-type stars now visible in the sky will shine on for at least another trillion years. The evolution of stars—large and small—is the subject of the next two chapters.

THE BIG QUESTION

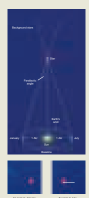
The *Hipparcos* satellite measured the detailed properties of hundreds of thousands of stars in the neighborhood of the Sun, greatly expanding our understanding of stellar properties and orbits in our Galaxy. In December 2013, the European Space Agency launched the GAIA mission, designed to extend the coverage of *Hipparcos* to roughly 1 billion objects, spanning a large portion of the entire Milky Way Galaxy. What new insights will GAIA yield? The impact on stellar and galactic astrophysics may be immeasurable.

CONCEPT CHECK

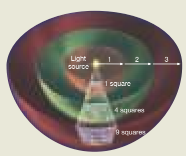
How do we know about the masses of stars that aren't members of binaries?

CHAPTER REVIEW

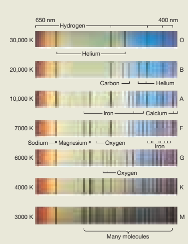
SUMMARY



LO1 The distances to the nearest stars can be measured by stellar parallax. A star with a parallax of 1 arc second is 1 **parsec** (p. 280)—about 3.3 light-years—away from the Sun. A star's **proper motion** (p. 282), which is its true motion across the sky, is a measure of the star's velocity perpendicular to our line of sight.

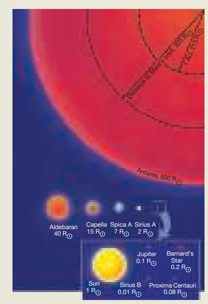


LO2 The **apparent brightness** (p. 282) of a star is the rate at which energy from the star reaches a detector. Apparent brightness is proportional to luminosity and falls off as the inverse square of the distance. Optical astronomers use the **magnitude scale** (p. 284) to express and compare stellar brightnesses. The greater the magnitude, the fainter the star; a difference of five magnitudes corresponds to a factor of 100 in brightness. **Apparent magnitude** (p. 284) is a measure of apparent brightness. The **absolute magnitude** (p. 284) of a star is the apparent magnitude it would have if placed at a standard distance of 10 pc from the viewer. It is a measure of the star's luminosity.

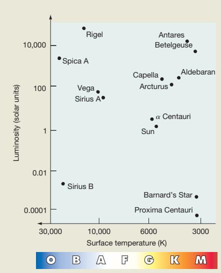


LO3 Astronomers often determine the temperatures of stars by measuring their brightnesses through two or more optical filters, then fitting a blackbody curve to the results. Spectroscopic observations of stars provide an accurate means of determining both stellar temperatures and stellar composition.

Astronomers classify stars according to the absorption lines in their spectra. The standard stellar **spectral classes** (p. 287), in order of decreasing temperature, are O B A F G K M.



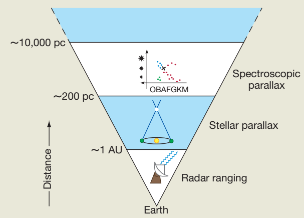
LO4 Only a few stars are large enough and close enough to Earth that their radii can be measured directly. The sizes of most stars are estimated indirectly through the **radius–luminosity–temperature relationship** (p. 289). Stars categorized as **dwarfs** (p. 289) are comparable in size to, or smaller than, the Sun; **giants** (p. 289) are up to 100 times larger than the Sun; and **supergiants** (p. 289) are more than 100 times larger than the Sun. In addition to "normal" stars such as the Sun, two other important classes of star are **red giants** (p. 289), which are large, cool, and luminous, and **white dwarfs** (p. 289), which are small, hot, and faint.



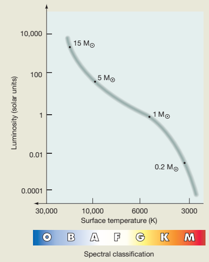
LO5 A plot of stellar luminosity versus stellar spectral class (or temperature) is called an **H–R diagram** (p. 289). About 90 percent of all stars plotted on an H–R diagram lie on the **main sequence** (p. 290), which stretches from hot, bright **blue supergiants** (p. 290) and **blue giants** (p. 290), through intermediate stars such as the Sun, to

cool, faint **red dwarfs** (p. 290). Most main-sequence stars are red dwarfs; blue giants are quite rare. About 9 percent of stars lie in the **white-dwarf region** (p. 291) and the remaining 1 percent lie in the **red-giant region** (p. 291).

LO6 If a star is known to lie on the main sequence, measurement of its spectral type allows its luminosity to be estimated and its distance to be measured. This method of distance determination, which is valid for stars up to several thousand parsecs from Earth, is called **spectroscopic parallax** (p. 293). A star's **luminosity class** (p. 294) allows astronomers to distinguish main-sequence stars from giants and supergiants of the same spectral type, making distance estimates much more reliable.



LO7 Most stars are not isolated in space but instead orbit other stars in **binary-star systems** (p. 295). In a **visual binary** (p. 295), both stars can be seen and their orbits charted. In a **spectroscopic binary** (p. 295), the stars cannot be resolved, but their orbital motion can be detected spectroscopically. In an **eclipsing binary** (p. 295), the orbits are oriented in such a way that one star periodically passes in front of the other as seen from Earth and dims the light we receive. Studies of binary stars often allow stellar masses to be measured. The mass of a star determines its size, temperature, and brightness. Hot blue giants are much more massive than the Sun; cool red dwarfs are much less massive. High-mass stars burn their fuel rapidly and have much shorter lifetimes than the Sun. Low-mass stars consume their fuel slowly and may remain on the main sequence for trillions of years.



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Problems labeled **POS** explore the process of science. **VIS** problems focus on reading and interpreting visual information. **LO** connects to the introduction's numbered Learning Outcomes.

REVIEW AND DISCUSSION

1. **LO1 POS** How is stellar parallax used to measure the distances to stars?
2. What is a parsec? Compare it to the astronomical unit.
3. Explain how a star's real motion through space translates into motion observable from Earth.
4. **LO4** Describe some characteristics of red giants and white dwarfs.
5. **LO2** What is the difference between absolute and apparent brightness?
6. **POS** How do astronomers measure star temperatures?
7. **LO3** Briefly describe how stars are classified according to their spectral characteristics.
8. **LO5** What information is needed to plot a star on the H–R diagram?
9. What is the main sequence? What basic property of a star determines where it lies on the main sequence?
10. **LO6** How are distances determined using spectroscopic parallax?
11. Which stars are most common in the Galaxy? Why don't we see many of them in H–R diagrams?
12. **LO7 POS** How can stellar masses be determined by observing binary-star systems?
13. High-mass stars start off with much more fuel than low-mass stars. Why don't high-mass stars live longer?
14. In general, is it possible to determine the life span of an individual star simply by noting its position on an H–R diagram?
15. Why are visual binaries and eclipsing binaries relatively rare compared to spectroscopic binaries?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. Star A appears brighter than star B, as seen from Earth. Therefore, star A must be closer to Earth than star B. (T/F)
2. A star of apparent magnitude +5 looks brighter than one of apparent magnitude + 2. (T/F)
3. Red giants are very bright because they are extremely hot. (T/F)
4. The radius of a star can be determined if the star's distance and luminosity are known. (T/F)
5. Astronomers can distinguish between main-sequence and giant stars by purely spectroscopic means. (T/F)
6. In a spectroscopic binary, the orbital motion of the component stars appears as variations in the overall apparent brightness of the system. (T/F)
7. There are no billion-year-old main-sequence O- or B-type stars. (T/F)
8. From a distance of 1 parsec, the angular size of Earth's orbit would be (a) 1 degree; (b) 2 degrees; (c) 1 arc minute; (d) 2 arc seconds.
9. Compared with a star of absolute magnitude –2 at a distance of 100 pc, a star of absolute magnitude 5 at a distance of 10 pc will appear (a) brighter; (b) fainter; (c) to have the same brightness; (d) bluer.
10. Stars of spectral class M do not show strong lines of hydrogen in their spectra because (a) they contain very little hydrogen; (b) their surfaces are so cool that most hydrogen is in the ground state; (c) their surfaces are so hot that most hydrogen is ionized; (d) the hydrogen lines are swamped by even stronger lines of other elements.
11. Cool stars can be very luminous if they are very (a) small; (b) hot; (c) large; (d) close to our solar system.

12. The mass of a star may be determined (a) by measuring its luminosity; (b) by determining its composition; (c) by measuring its Doppler shift; (d) by studying its orbit around a binary companion.

13. VIS Pluto's apparent magnitude is approximately 14. According to Figure 10.6 (Apparent Magnitude), Pluto can be seen (a) with the naked eye on a dark night; (b) using binoculars; (c) using a 1-meter telescope; (d) only with the *Hubble Space Telescope*.

14. VIS According to Figure 10.12 (H–R Diagram of Well-Known Stars), Barnard's star must be (a) hotter; (b) larger; (c) closer to us; (d) bluer than Proxima Centauri.

15. VIS According to Figures 10.19 (Stellar Masses) and 10.20 (Stellar Mass Distribution), compared to the Sun, most stars are (a) much hotter; (b) much cooler; (c) much larger; (d) much brighter.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ How far away is the star Spica, whose parallax is 0.013″? What would Spica's parallax be if it were measured from an observatory on Neptune's moon Triton as Neptune orbited the Sun?

2. ■■ A star lying 20 pc from the Sun has proper motion of 0.5″ /yr. What is its transverse velocity? If the star's spectral lines are observed to be redshifted by 0.01 percent, calculate the magnitude of its three-dimensional velocity relative to the Sun.

3. ■■ (a) What is the luminosity of a star having three times the radius of the Sun and a surface temperature of 10,000 K? (b) A certain star has a temperature twice that of the Sun and a luminosity 64 times greater than the solar value. What is its radius, in solar units?

4. ■■ Two stars—A and B, of luminosities 0.5 and 4.5 times the luminosity of the Sun, respectively—are observed to have the same apparent brightness. Which star is more distant, and how much farther away is it than the other?

5. ■■ Two stars—A and B with absolute magnitudes 3 and 8, respectively—are observed to have the same apparent magnitude. Which star is more distant, and how much farther away is it than the other?

6. ■■ Calculate the amount of energy received per unit area per unit time from the sun, as seen from a distance of 10 pc. Compare this with the solar constant at Earth. ∞ *(Sec. 9.1)*

7. ■ Astronomical objects visible to the naked eye range in apparent brightness from faint sixth-magnitude stars to the Sun, with magnitude –27. What is the range in energy flux corresponding to this magnitude range?

8. ■ A star has apparent magnitude 10.0 and absolute magnitude 2.5. How far away is it?

9. ■■■ Two stars in an eclipsing spectroscopic binary system are observed to have an orbital period of 25 days. Further observations reveal that the orbit is circular, with a separation of 0.3 AU, and that one star is 1.5 times the mass of the other. What are the masses of the stars?

10. ■■ Given that t he Sun's lifetime is about 10 billion years, estimate the life expectancy of (a) a 0.2-solar mass, 0.01-solar luminosity red dwarf; (b) a 3.0-solar mass, 30-solar luminosity star; (c) a 10-solar mass, 1000-solar luminosity blue giant.

ACTIVITIES

Collaborative

1. Estimate the total number of stars visible in the night sky. Each member of your group should be equipped with identical cardboard tubes—the tube at the center of a roll of paper towels or toilet paper is perfect for the task. On a clear, moonless night, hold your tube up to your eye and count the total number of stars you can see. Do this several times, randomly choosing different areas of the sky and avoiding obvious obstacles such as clouds and trees. Try to sample all directions roughly equally. Be sure to allow time for your eyes to adapt to the dark—10 to 15 minutes at least—before taking any measurements. Add up all your measurements and divide by the total number of observations to calculate the average number of stars observed—call it n. You can convert this number into an estimate of the total number N of visible stars by multiplying by the square of the ratio of the length L of the tube to its diameter D, that is: $N = (L/D)^2 \times n$. (Can you figure out where this formula came from?) Repeat your measurement at a variety of sites—a city, the suburbs, and a dark rural location. Can you understand why astronomers are so concerned about light pollution?

Individual

1. The Winter Circle is an asterism—or pattern of stars—made up of six bright stars in five different constellations: Sirius, Rigel, Betelgeuse, Aldebaran, Capella, and Procyon. These stars span nearly the entire range of colors (and therefore temperatures) of normal stars. Rigel is of type B; Sirius, A; Procyon, F; Capella, G; Aldebaran, K; and Betelgeuse, M. The color differences are easy to see. Why do you suppose there is no O-type star in the Winter Circle?

2. In the winter sky, find the red supergiant Betelgeuse in the constellation Orion. It's easy to see because it's one of the brightest stars in the entire night sky. Betelgeuse is a variable star with a period of about 6.5 years. Its brightness changes as it expands and contracts. At maximum size, it fills a volume of space that would extend from the Sun to beyond the orbit of Jupiter. Betelgeuse is thought to be about 10 to 15 times more massive than our Sun and probably between 4 and 10 million years old. A similar star can be found shining prominently in midsummer. This is the red supergiant Antares in the constellation Scorpius.

11

The Interstellar Medium

Star Formation in the Milky Way

Stars and planets are not the only inhabitants of our Galaxy. The space around us harbors invisible matter throughout the dark voids between the stars. The density of this interstellar matter is extremely low—approximately a trillion trillion times less dense than matter in either stars or planets, far thinner than the best vacuum attainable on Earth. Only because the volume of interstellar space is so vast does the mass of interstellar matter amount to anything at all. Why bother to study this near-perfect vacuum? We do so for three important reasons. First, there is as much mass in the "voids" between the stars as there is in the stars themselves. Second, interstellar space is the region out of which new stars are born. Third, it is the region into which old stars expel their matter when they die. It is one of the most significant crossroads through which matter passes in the history of our universe.

THE BIG PICTURE

Few questions in astronomy are more basic than asking how stars form. Stars are the most numerous and obvious residents of the nighttime sky—just look up on any clear night. Astronomers are eager to understand the details of how stars emerge from the dark depths of interstellar space to become bright round balls of intense energy. The process is a remarkable one, and we have learned much about it during the past few decades.

◂ This *Hubble Space Telescope* image of the young star cluster Westerlund 2 combines visible-light and near-infrared exposures of the cluster itself (right center), with visible-light observations of the surrounding gas out of which it formed. The cluster is about 3000 times the mass of the Sun, but the interstellar gas in its vicinity is much more massive. The intense radiation from young stars in the cluster is sculpting and heating the nearby gas, dispersing it into space and possibly triggering new episodes of star formation.

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Summarize the composition and properties of interstellar matter.
- **LO2** Describe the characteristics of emission nebulae, and explain their connection with star formation.
- **LO3** Outline the properties of dark interstellar dust clouds and molecular clouds.
- **LO4** Specify some of the radio techniques used to probe the nature of interstellar gas.
- **LO5** Summarize the sequence of events leading from a cold, dense interstellar cloud to the formation of a star like our Sun.
- **LO6** Describe some of the observational evidence supporting the modern theory of star formation.
- **LO7** Explain how the formation of a star depends on its mass.
- **LO8** Describe the properties of star clusters, and discuss how they form.

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DATA POINTS

Interstellar Gas

Sixty percent of students had difficulty describing and distinguishing the properties of interstellar gas clouds. Some key points to remember:

- Dark dust clouds are cool regions of gas that emit no visible light and absorb visible light from stars behind them. They emit radiation primarily in the radio and infrared parts of the electromagnetic spectrum.
- Emission nebulae are hot regions of gas surrounding newborn stars. They emit visible light.
- Emission nebulae are often found embedded in dark dust clouds in which stars are forming.

11.1 Interstellar Matter

Figure 11.1 is a mosaic of photographs covering a much greater expanse of universal "real estate" than anything we have studied thus far. From our vantage point on Earth, the panoramic view shown here stretches all the way across the sky. On a clear night it is visible to the naked eye as the *Milky Way.* In Chapter 14 we will come to recognize this band as the flattened disk, or *plane,* of our own Galaxy.

The bright regions in this image are made up of innumerable unresolved distant stars, merging together into a continuous blur at the resolution of the telescope. However, the dark areas are not simply "holes" in the stellar distribution. They are regions of space where *interstellar matter* obscures the light from stars beyond, blocking from our view what would otherwise be a smooth distribution of bright starlight. In this chapter we focus not on the stars themselves but also on the vast reaches of interstellar space in which they form.

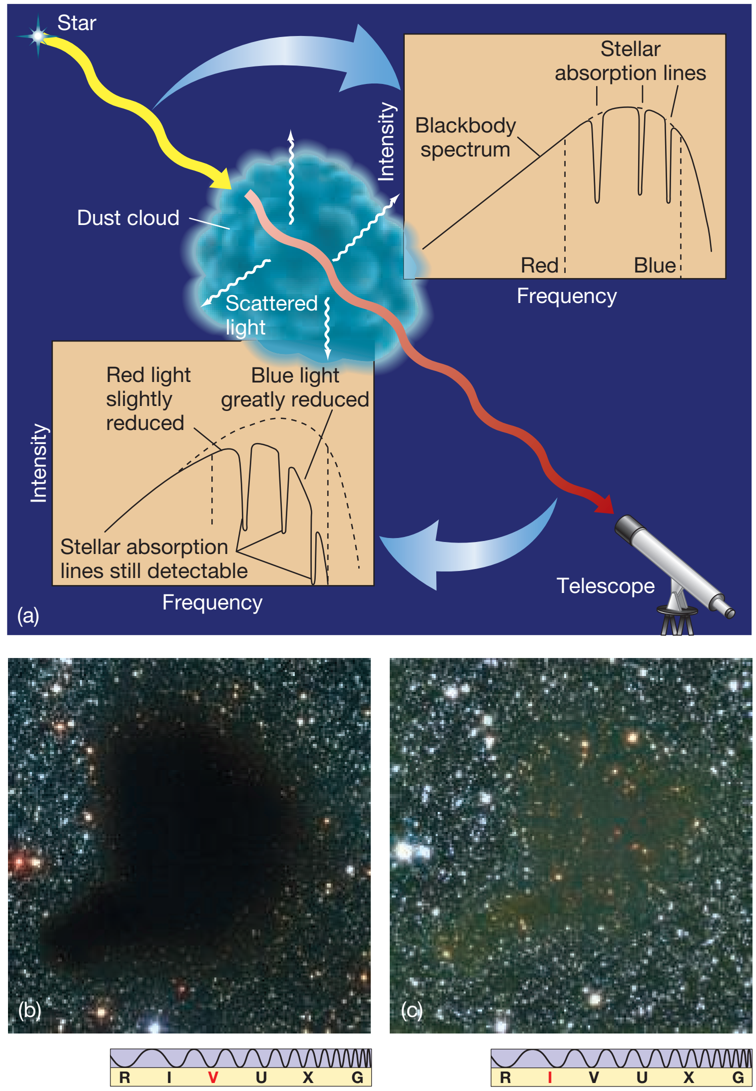
Gas and Dust

The matter between the stars is collectively termed the **interstellar medium.** It is made up of two components—*gas* and *dust*—intermixed throughout all of space. The gas is made up mainly of individual atoms and small molecules. The dust consists of clumps of atoms and molecules—not unlike the microscopic particles that make up smoke or soot.

Apart from numerous narrow atomic and molecular absorption lines, the gas alone does not block electromagnetic radiation to any great extent. The patchy obscuration evident in Figure 11.1 is caused by dust. Light from distant stars cannot penetrate the densest accumulations of interstellar dust any more than a car's headlights can illuminate the road ahead in a thick fog. As a rule of thumb, a beam of light can be absorbed or scattered only by particles having diameters comparable to or larger than the wavelength of the radiation involved. The amount of obscuration (absorption or scattering) produced by particles of a given size increases with decreasing wavelength. The typical diameter of an interstellar dust

▼ FIGURE 11.1 **Milky Way Mosaic** The Milky Way photographed panoramically, across 360° of the entire southern and northern celestial sphere. This band, which constitutes the central plane of our Galaxy, contains high concentrations of stars, as well as interstellar gas and dust. The gray box outlines the field of view of Figure 11.4. *(ESO/S. Brunier)*

▶ **FIGURE 11.2 Reddening** (a) Starlight passing through a dusty region of space is both dimmed and reddened, but spectral lines are still recognizable in the light that reaches Earth. (b) This dusty interstellar cloud, called Barnard 68, is opaque to visible light, except near the edges. The cloud spans about 0.2 pc and lies about 160 pc away. Frame (c) illustrates (in false color) how infrared radiation can penetrate Barnard 68. *(ESO)*



particle—or **dust grain**—is about 10^{-7} m comparable in size to the wavelength of visible light. Consequently, dusty regions of interstellar space are transparent to long-wavelength radio and infrared radiation but opaque to shorter-wavelength optical, ultraviolet, and X-ray radiation.

Because the opacity of the interstellar medium increases with decreasing wavelength, light from distant stars is preferentially robbed of its higher-frequency ("blue") components. Hence, in addition to being generally diminished in overall brightness, stars also appear redder than they really are. Illustrated in Figure 11.2, this effect, known as **reddening**, is similar to the process that produces spectacular red sunsets here on Earth (see Figure 11.3). Reddening can be seen very clearly in Figure 11.2(b), which shows a type of compact, dusty interstellar cloud called a *globule*. (We will discuss such dark interstellar clouds in more detail in Section 11.3.) The center of this cloud, called Barnard 68, is opaque to all optical wavelengths, so starlight cannot pass through it. However, near the edges, where there is less intervening cloud matter, some light does make it through; in the infrared image of Figure 11.2(c), even more radiation gets through. Notice how stars seen through the cloud are both dimmed and reddened relative to those seen directly.

As indicated in Figure 11.2(a), absorption lines in a star's spectrum are still recognizable in the radiation reaching Earth, allowing the star's spectral class, and hence its true luminosity and color, to be determined. ∞ *(Sec. 10.6)* Astronomers can then measure the degree to which the star's light has been dimmed and reddened en route to Earth, allowing them to estimate the amount of dust along the line of sight.

◄ **FIGURE 11.3 Reddening in Earth's Atmosphere** Sunlight is reddened as it passes through Earth's atmosphere at the end of a hot summer day. Airborne dust particles and water molecules scatter the Sun's blue light, leaving only its dimmed, red light—a spectacular sunset. *(Joyce Photographics)*

Density and Composition of the Interstellar Medium

By measuring its effect on the light from many different stars, astronomers have built up a picture of the distribution and chemical properties of interstellar matter in the solar neighborhood.

Gas and dust are found everywhere in interstellar space. No part of our Galaxy is truly devoid of matter, although the density of the interstellar medium is extremely low. Overall, the gas averages roughly 10^6 atoms per cubic meter—just one atom per cubic centimeter. (For comparison, the best vacuum presently attainable in laboratories on Earth contains about 10^9 atoms per cubic meter.) Interstellar dust is even rarer—about one dust particle for every trillion or so atoms. The space between the stars is populated with matter so thin that harvesting all

11.1 DISCOVERY

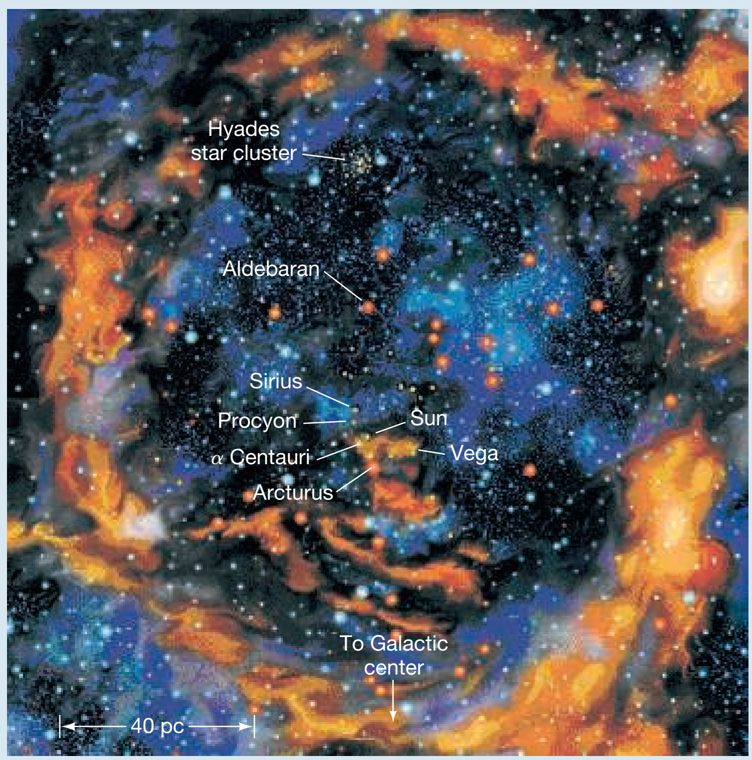
Ultraviolet Astronomy and the "Local Bubble"

The ultraviolet (UV) region is that part of the spectrum where we expect to witness events and see objects involving temperatures in the hundreds of thousands, even millions, of kelvins—hot regions like the seething atmospheres or eruptive flares of stars; violent events, such as massive stars caught in the act of exploding; and active galaxies whose spinning hearts may harbor black holes. Yet ultraviolet astronomy has also contributed greatly to the study of the interstellar medium, by allowing a unique mapping of our local cosmic neighborhood.

Only 30 years ago astronomers had presumed that the gases filling the spaces among the stars would absorb virtually all short-wavelength UV radiation before it had a chance to reach Earth. But in 1975, during a historic linkup of the *Apollo* (U.S.) and *Soyuz* (USSR) space capsules, the onboard astronauts and cosmonauts performed a key experiment—they used a small telescope to detect extreme ultraviolet radiation from a few nearby, very hot stars. Shortly thereafter, theoretical ideas changed as astronomers began to realize that interstellar gas is distributed very unevenly in space, in cool dense clumps interspersed by irregularly shaped regions of hot, low-density gas.

Since then, space-based ultraviolet observations have shown that some regions of interstellar space are much thinner (5000 atoms/m^3) and hotter (500,000 K) than previously expected. Part of the space among the dust clouds and the emission nebulae seems to contain extremely dilute yet seething plasma, probably the result of the concussion and expanding debris from stars that exploded long ago. These superheated interstellar "bubbles," or *intercloud medium,* may extend far into interstellar space beyond our local neighborhood and conceivably into the even vaster spaces among the galaxies.

The Sun seems to reside in one such low-density region—a huge cavity called the *Local Bubble,* sketched in the accompanying figure. Only because we live within this vast, low-density bubble can we detect so many stars in the far UV; the hot, tenuous interstellar gas is virtually transparent to this radiation. The Local Bubble contains about 200,000 stars and extends for hundreds of trillions of kilometers, or nearly 100 pc. It was probably carved out by a supernova explosion that occurred in these parts roughly 300,000 years ago (see Section 12.4). Our distant ancestors must have seen it—a stellar catastrophe as bright as the full Moon.



(Rice University/NASA)

the gas and dust in an interstellar region the size of Earth would yield barely enough matter to make a pair of dice.

Despite such low densities, over sufficiently large distances interstellar matter accumulates slowly but surely to the point where it can block visible light and other short-wavelength radiation from distant sources. All told, space in the vicinity of the Sun contains about as much mass in the form of interstellar gas and dust as exists there in the form of stars.

Interstellar matter is distributed very unevenly (see *Discovery 11-1*). In some directions it is largely absent, allowing astronomers to study objects literally billions of parsecs from the Sun. In other directions there are small amounts of interstellar matter, so the obscuration is moderate, preventing us from seeing objects more than a few thousand parsecs away, but allowing us to study nearby stars. Still other regions are so heavily obscured that starlight from even relatively nearby stars is completely absorbed before reaching Earth. Even in regions of dense obscuration, however, there are often "windows" through which we can see to great distances—several can be seen in Figure 11.1.

The composition of interstellar gas is reasonably well known from spectroscopic studies of interstellar absorption lines. ∞ *(Sec. 2.5)* It mirrors the composition of other astronomical objects, such as the Sun, the stars, and the Jovian planets: Most of the gas—about 90 percent—is atomic or molecular hydrogen, 9 percent is helium, and the remaining 1 percent consists of heavier elements. The gas is deficient in some heavy elements, such as carbon, oxygen, silicon, magnesium, and iron, most likely because these elements have gone to form the interstellar dust.

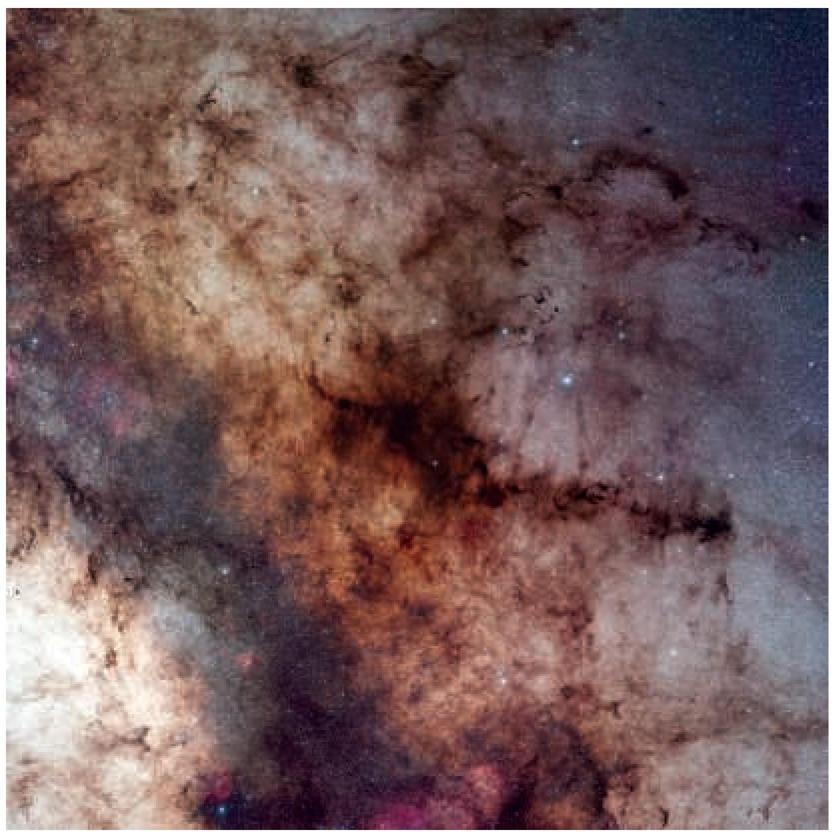
In contrast, the composition of the dust is not well known, although there is some infrared evidence for silicates, carbon, and iron, supporting the theory that interstellar dust forms out of interstellar gas. The dust probably also contains some "dirty ice," a frozen mixture of water ice contaminated with trace amounts of ammonia, methane, and other compounds, much like cometary nuclei in our own solar system. ∞ *(Sec. 4.2)*

CONCEPT CHECK

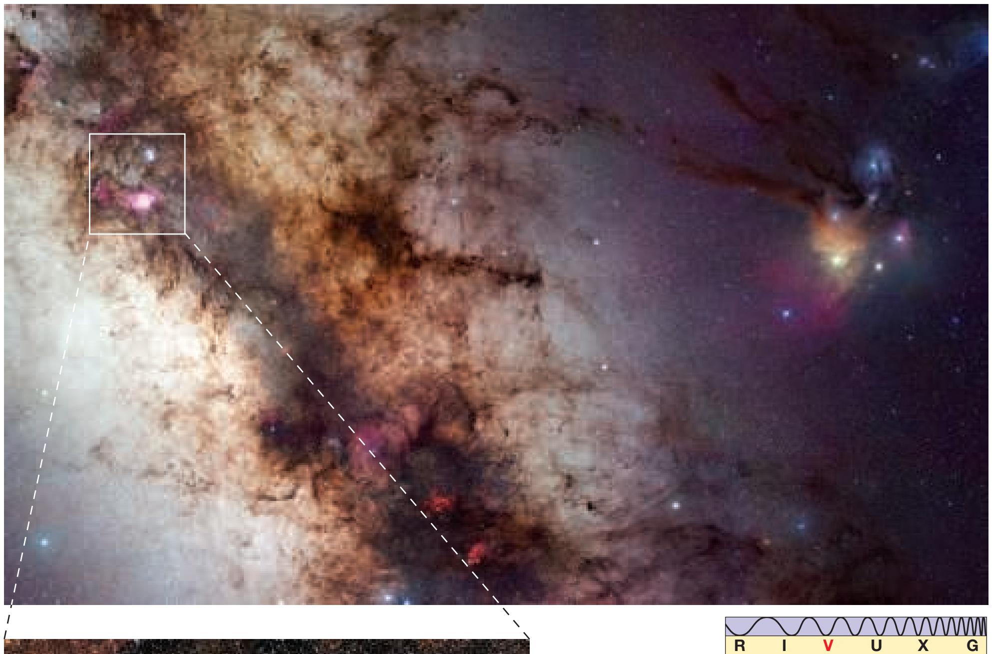
If space is a near-perfect vacuum, how can there be enough dust in it to block starlight?

11.2 Star-Forming Regions

Figure 11.4 shows a magnified view of the central part of Figure 11.1, in the general direction of the constellation Sagittarius. The field of view is mottled with innumerable stars and dark foreground interstellar matter. Historically, astronomers have used the term **nebula** (plural: nebulae) to refer to any "fuzzy" patch (dark or bright) on the sky—any region of space that is clearly distinguishable through a telescope, but not sharply defined, unlike a star or a planet. We now know that many (although by no means all) nebulae are clouds of interstellar dust and gas. If such a cloud happens to obscure stars lying behind it, then we see it as a dark patch on a bright background, as in Figure 11.2(b)—a *dark nebula*. But if something within the cloud—a group of hot young stars, for example—causes it to glow, we see something very different.

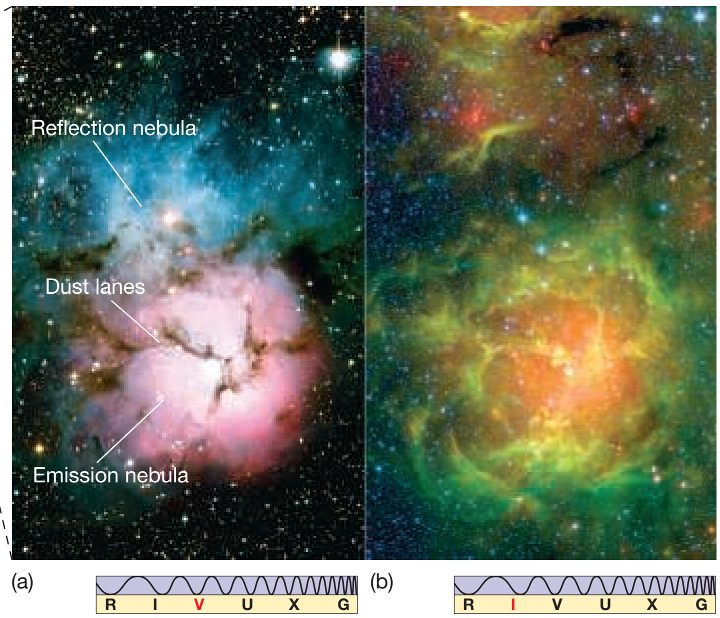


▶ **FIGURE 11.4 Star Field in Sagittarius** This enlargement of the central portion of Figure 11.1, shows regions of brightness (vast fields of stars) as well as regions of darkness (where interstellar matter obscures the light from more distant stars). The field of view is about 10° across. *(ESO/S. Guisard)*



◀ **FIGURE 11.5 Galactic Plane** This 35° wide swath of the sky near the center of the Milky Way corresponding to the gray rectangle on Figure 11.1 shows stars, gas, and dust, as well as several distinct fuzzy patches of light known as emission nebulae. *(Harvard College Observatory)*

▲ **FIGURE 11.6 M20–M8 Region** A true-color enlargement of the bottom of Figure 11.5, showing M20 (top) and M8 (bottom) more clearly. *(R. Gendler)*



▲ **FIGURE 11.7 Trifid Nebula** (a) Further enlargement of the top of Figure 11.6, showing only M20 and its interstellar environment. Called the Trifid Nebula because of the dust lanes (in black) that trisect its midsection, the nebula itself (in red) is about 20 light-years across. (b) A false-color infrared image taken by the *Spitzer Space Telescope* reveals bright regions of star-forming activity mostly in those lanes of dust. *(NASA)*

Figure 11.5 expands the field of view of Figure 11.4. The approximate location of this 30 degree swath relative to the Milky Way is indicated by the gray rectangle in Figure 11.1. In addition to stars and dark nebulae, two fuzzy patches of light are visible near the top of the figure. Labeled M8 and M20, they correspond to the 8th and 20th entries in a catalog compiled by Charles Messier, an 18th-century French astronomer. They are called **emission nebulae**—glowing clouds of hot interstellar gas surrounding groups of young, bright stars. Two more emission nebulae (with catalog names NGC 6334 and NGC 5357) can be seen at bottom center. The method of spectroscopic parallax applied to stars visible within these nebulae indicates that their distances from Earth range from 1200 pc (M8) to 2400 pc (NGC 5357) ∞ *(Sec. 10.6)*.

We can gain a better appreciation of these nebulae by examining progressively smaller fields of view. Figure 11.6 is an enlargement of the region near the bottom of Figure 11.5, showing M20 at the top and M8 at the bottom. Figure 11.7 further enlarges the top of Figure 11.6, presenting a close-up of M20 and its immediate environment in both the visible and infrared parts of the spectrum. The total area displayed measures some 12 pc across. Emission nebulae are among the most spectacular objects in the universe, yet they appear only as small, undistinguished patches of light when viewed in the larger context of the Milky Way. Perspective is crucial in astronomy.

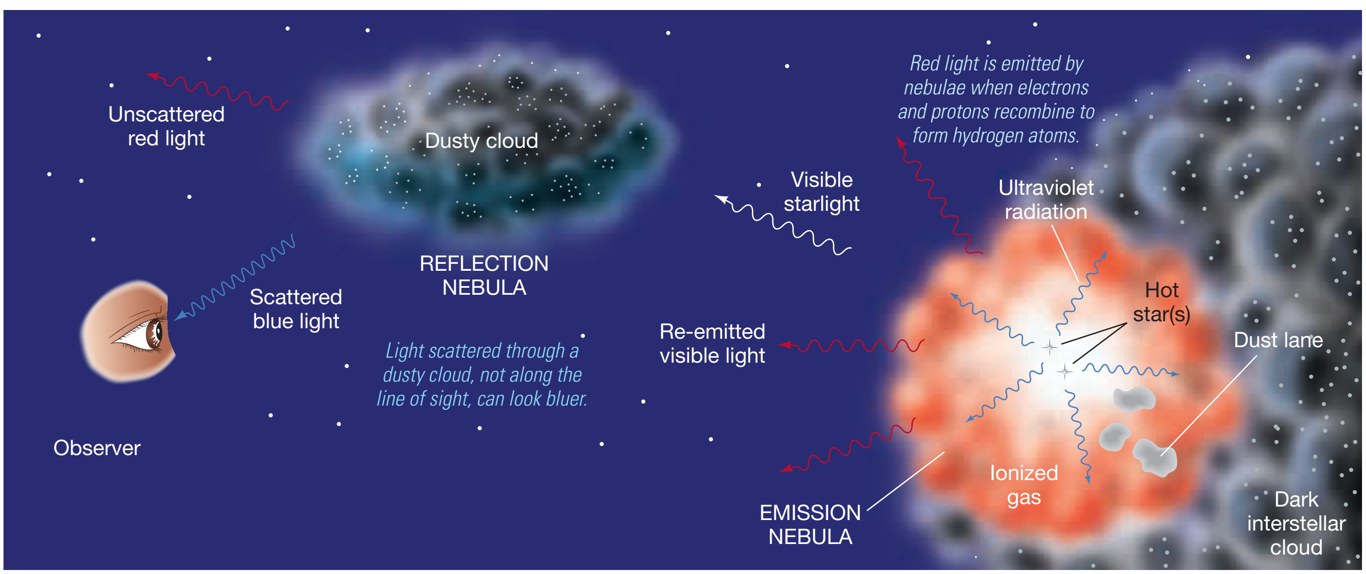
The nebulae shown in Figures 11.4–11.7 are regions of glowing, ionized gas. At or near the center of each is at least one newly formed hot O- or B-type star producing copious amounts of ultraviolet light. As ultraviolet photons travel outward from the star, they heat and ionize the surrounding gas. As electrons recombine with nuclei, they emit visible radiation, causing the gas to glow. The predominant red coloration is the result of hydrogen atoms emitting Hα light in the red part of the visible spectrum. ∞ *(Sec. 2.6)*

Woven through the glowing nebular gas, and plainly visible in Figures 11.5–11.7, are dark **dust lanes** obscuring the nebular light. These dust lanes are part of the nebulae and are not just unrelated dust clouds that happen to lie along our line of sight. The bluish region visible in Figure 11.7 immediately above M20 is another type of nebula unrelated to the red emission nebula itself. Called a *reflection nebula,* it is caused by starlight reflecting off intervening dust particles along the line of sight. The blue coloration occurs because short-wavelength blue light is more easily scattered by interstellar matter back toward Earth and into our detectors. Figure 11.8 sketches some of the key features of emission nebulae, illustrating the connection between the central stars, the nebula itself, and the surrounding interstellar medium.

Figure 11.9 shows two other nebulae (located just outside the top-left corner of Figure 11.5). Notice again the hot bright stars embedded within the glowing nebular gas and the overall red hue of the reemitted radiation in parts (a) and (c). (The colors in the *Hubble* images parts [b] and [d] accentuate observations made at different wavelengths.) The relationship between the nebula and the dust lanes

MA INTERACTIVE
Multiwavelength Cloud with Embedded Stars

▼ **FIGURE 11.8 Nebular Structure** An emission nebula results when ultraviolet radiation from one or more hot stars ionizes part of an interstellar cloud. If starlight happens to encounter another dusty cloud, some of the radiation, particularly at the shorter wavelength blue end of the spectrum, may be scattered back toward Earth, forming a reflection nebula.



ANIMATION / VIDEO
Gaseous Pillars of Star Birth

▲ **FIGURE 11.9 Emission Nebulae** (a) M16, the Eagle Nebula and (b) a close-up of its huge pillars of cold gas and dust within, showing delicate sculptures created by the action of stellar ultraviolet radiation on the original cloud. (c) M8, the Lagoon Nebula and (d) a high-resolution view of its core, a region known as the Hourglass. The varied colors of the insets result from observations at different wavelengths. Both these nebulae lie in the Milky Way plane, just to the upper left of the field of view of Figure 11.5. *(NASA/AURA/ESO)*

is again evident in Figure 11.9 (b) and (d), where regions of gas and dust are simultaneously silhouetted against background nebular emission and illuminated by foreground nebular stars. The interaction between stars and gas is particularly striking in Figure 11.9(b). The three dark "pillars" visible in this spectacular image are part of the interstellar cloud from which the stars formed. The rest of the cloud in the vicinity of the new stars has already been dispersed by their radiation. The fuzz around the edges of the pillars, especially at top right and center, is the result of this ongoing process, where intense stellar radiation continues to "eat away" the cloud, heating and dispersing the dense molecular gas. The process removes the less dense material first, leaving behind delicate sculptures composed of the denser parts of the original cloud, much as wind and water create spectacular

TABLE 11.1 Nebular Properties

Object	Approx Distance (pc)	Average Diameter (pc)	Density (10^6 particles/m^3)	Mass (Solar Masses)	Temperature (K)
M8	1200	14	80	2600	7500
M16	1800	8	90	600	8000
M17	1500	7	120	500	8700
M20	1600	6	100	250	8200

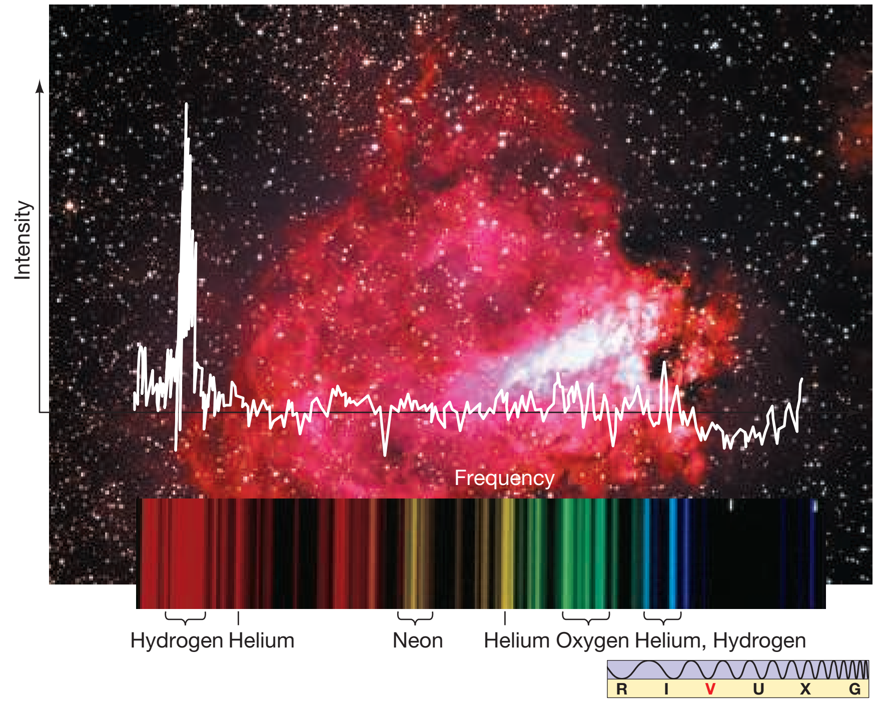
CONCEPT CHECK

If emission nebulae are powered by ultraviolet light from hot stars, why do they appear red?

structures in Earth's deserts and shores by eroding away the softest rock. The pillars will eventually be destroyed, but probably not for another hundred thousand or so years.

Table 11.1 lists some vital statistics for some of the nebulae shown in this section. Unlike stars, nebulae are large enough for their sizes to be measurable by simple geometry. ∞ *(More Precisely 4-1)* Coupling this size information with estimates of the amount of matter along our line of sight (as revealed by absorption of the nebula's light), we can find a nebula's density. Emission nebulae typically contain a few hundred particles per cubic centimeter (10^8 per cubic meter), mostly protons and electrons. Figure 11.10 shows the emission nebula M17, along with its spectrum at visible and near-ultraviolet wavelengths. ∞ *(Sec. 2.5)*. Numerous emission lines can be seen, providing further information on the nebula. Analyses of such spectra reveal nebular compositions similar to the Sun and other stars, as well as elsewhere in the interstellar medium. Spectral line widths imply temperatures of around 8000 K. ∞ *(Sec. 2.8)*

▼**FIGURE 11.10 Nebular Spectrum** The visible spectrum of the hot gases in a nearby star-forming region known as the Omega Nebula (M17). Shining by the light of several very hot stars, the nebula produces a complex spectrum of bright and dark lines (bottom), also shown here as an intensity trace from red to blue (center). *(ESO)*



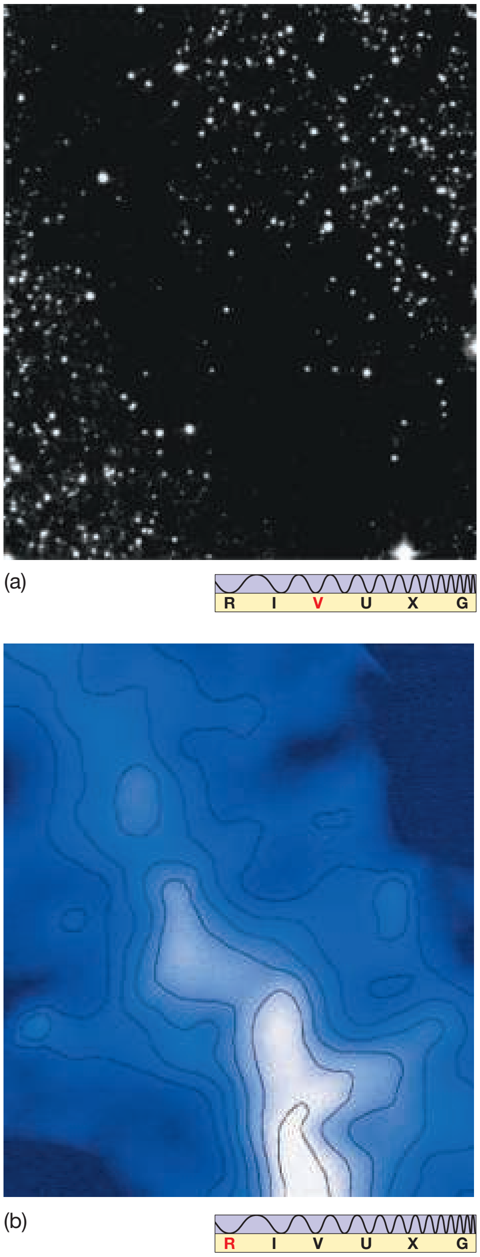
11.3 Dark Dust Clouds

Emission nebulae are only one small component of interstellar space. Most of space—in fact, more than 99 percent of it—is devoid of such regions and contains no stars. It is simply dark. The average temperature of a typical dark region of interstellar space is about 100 K. Compare this with 273 K, at which water freezes, and 0 K, at which atomic and molecular motions cease. ∞ *(More Precisely 2-1)*

Within the dark voids among the nebulae and the stars lurks another distinct type of astronomical object, the **dark dust cloud.** These clouds are cooler than their surroundings, with temperatures as low as a few tens of kelvins, and thousands or even millions of times denser. In some regions, densities exceeding 10^9 atoms/m^3 (1000 atoms/cm^3) are found. Researchers often refer to dark dust clouds as *dense* interstellar clouds, but recognize that even these densest interstellar regions are barely denser than the best vacuum achievable in terrestrial laboratories. Still, it is because their density is much larger than the average value of 10^6 atoms/m^3 in interstellar space that we can distinguish these clouds from the surrounding expanse of the interstellar medium.

Obscuration of Visible Light

Dark dust clouds bear little resemblance to terrestrial clouds. Most are bigger than our solar system, and some are many parsecs across, although they still make up no more than a few percent of the entire volume of interstellar space. Despite their name, these clouds are composed primarily of gas, just like the rest



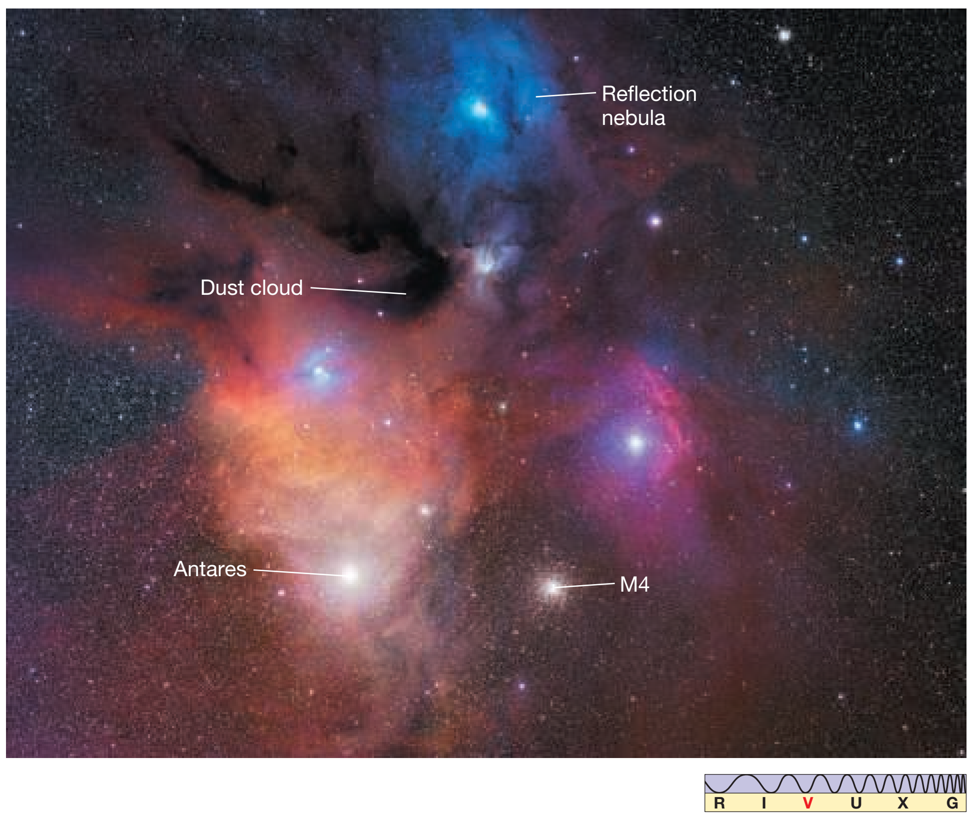
▲ **FIGURE 11.11 Obscuration and Emission** (a) At optical wavelengths, this dark dust cloud (known as L977) can be seen only by its obscuration of background stars. (b) At radio wavelengths, it emits strongly in the CO molecular line, with the most intense radiation coming from the densest part of the cloud. *(C. and E. Lada)*

of the interstellar medium. However, their absorption of starlight is due almost entirely to the dust they contain.

Figure 11.2(b) is a good example of a dark dust cloud. Figure 11.11(a), a region called L997 in the constellation Cygnus, is another. Some early (18th-century) observers thought that these dark patches on the sky were simply empty regions of space that happened to contain no bright stars. However, by the late 19th century, astronomers had discounted this idea. They realized that seeing clear spaces among the stars would be like seeing clear tunnels between the trees in a forest, and it was statistically impossible that so many tunnels would lead directly away from Earth.

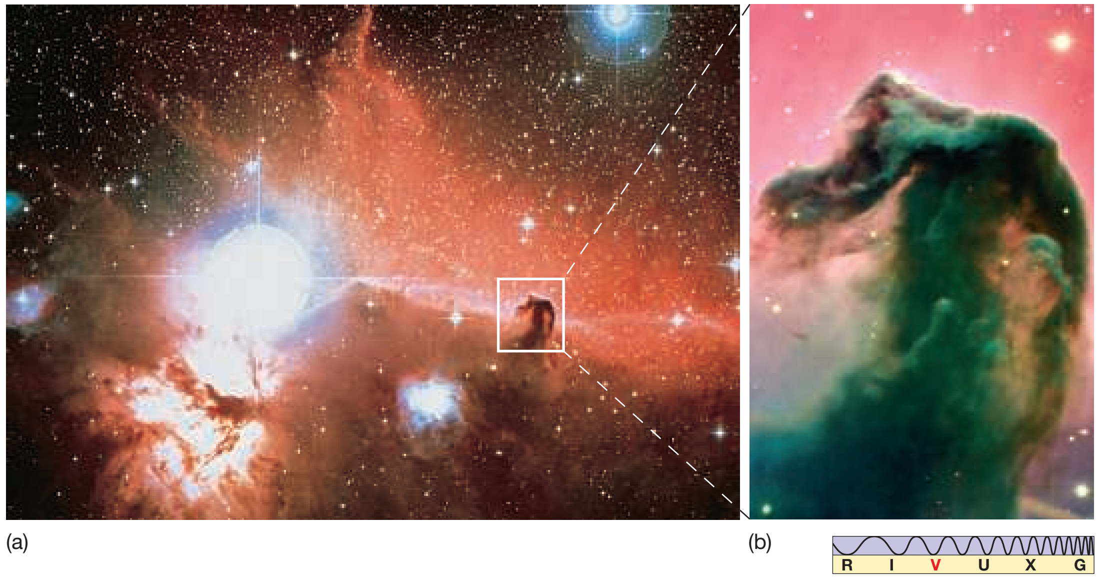
Before the advent of radio astronomy, astronomers had no direct means of studying clouds like L977. Emitting no visible light, they are generally undetectable to the eye except by the degree to which they dim starlight. However, as shown in Figure 11.11(b), the cloud's radio emission—in this case from carbon monoxide (CO) molecules contained within its volume—outlines it clearly at radio wavelengths, providing an indispensable tool for the study of such objects.

Figure 11.12 is a spectacular wide-field image of another dark dust cloud. Taking its name from a neighboring star system, Rho Ophiuchus, this dust cloud resides relatively nearby, making it one of the most intensely studied regions of star formation in the Milky Way. Pockets of heavy blackness mark regions where the dust and gas are especially concentrated and the light from the background stars is completely obscured. Measuring several parsecs across, the Ophiuchus cloud is also visible on the right side of Figure 11.5. Note that this cloud, like most interstellar clouds, is very irregularly shaped. Some of the features labeled in the image are part of the cloud itself, whereas others are newly formed stars near the edge of the cloud. Still other objects have no connection to the cloud and just happen to lie along the line of sight.



▶ **FIGURE 11.12 Dark Dust Cloud** The Ophiuchus dark dust cloud resides only 170 pc away, surrounded by colorful stars and nebulae that are actually small illuminated parts of a much bigger and invisible molecular cloud engulfing much of the region shown. *(R. Gendler/J. Misti/S. Mazlin)*

Figure 11.13 shows a particularly striking and well-known example of a dark dust cloud—the Horsehead Nebula in Orion. This curiously shaped finger of gas and dust projects out from the much larger dark cloud in the bottom half of the image and stands out clearly against the red glow of a background emission nebula.



▲ **FIGURE 11.13 Horsehead Nebula** (a) The Horsehead Nebula is a striking example of a dark dust cloud, silhouetted against the bright background of an emission nebula. (b) A stunning image of the Horsehead, taken at highest resolution by the Very Large Telescope (VLT) in Chile. *(Sec. 3.2)* The "neck" of the horse is about 0.25 pc across. This nebular region lies roughly 1500 pc from Earth, in the constellation Orion. *(Royal Observatory of Belgium; ESO)*

21-Centimeter Radiation

Often, dark dust clouds absorb so much light from background stars that they cannot easily be studied by the optical techniques described in Section 11.1. Fortunately, astronomers have an important alternative means of probing their structure that relies on low-energy radio emission from the interstellar gas itself.

Much of the gas in interstellar space is atomic hydrogen. Recall that a hydrogen atom consists of one electron orbiting a single-proton nucleus. ∞ *(Sec. 2.6)* Besides its orbital motion around the central proton, the electron also has some rotational motion—that is, *spin*—about its own axis. The proton also spins. This model parallels a planetary system, in which, in addition to the orbital motion of a planet about a central star, both the planet (electron) and the star (proton) rotate about their axes.

The laws of physics dictate that there are just two possible spin configurations for a hydrogen atom in its ground state. As illustrated in Figure 11.14, the electron and proton can either rotate in the *same* direction, with their spin axes parallel, or they can rotate in *opposite* directions, with their axes parallel but oppositely oriented. The former configuration has slightly higher energy than the latter. When a slightly excited hydrogen atom having the electron and proton spinning in the same direction drops down to the less-energetic, opposite-spin state, the transition releases a photon with energy equal to the energy difference between the two states.

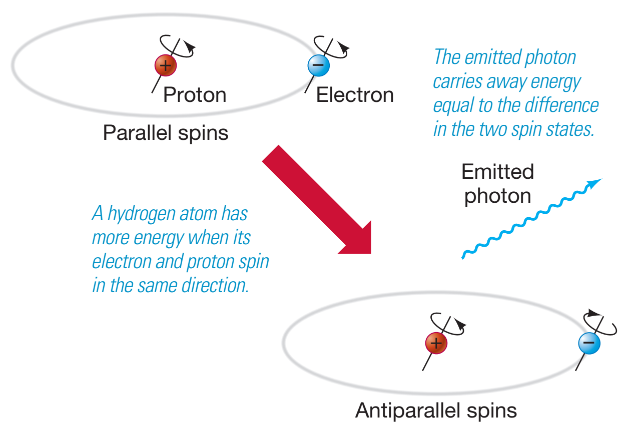
Because the energy difference between the two states is very small, the energy of the emitted photon is very low. ∞ *(Sec. 2.6)* Consequently, the wavelength of the radiation is long—about 21 cm. That wavelength lies in the radio portion of the electromagnetic spectrum. Researchers refer to the spectral emission line that results from this hydrogen–spin-flip process as the **21-centimeter line.** It provides a vital probe into any region of the universe containing atomic hydrogen gas. Needing no visible starlight to help calibrate their signals, radio astronomers can observe any interstellar region that contains enough hydrogen to produce a detectable signal. Even the low-density regions between dark dust clouds can be studied.

Of great importance is the fact that the wavelength of 21-cm radiation is much larger than the typical size of interstellar dust particles. Accordingly, this radio radiation reaches Earth completely unaffected by interstellar debris. The opportunity to observe interstellar space well beyond a few thousand parsecs, and in directions lacking detectable background stars, makes 21-cm observations among the most important and useful tools in all of astronomy. As we will see in Chapters 10 and 15, it has been indispensable in allowing astronomers to map out the large-scale structure of our own galaxy and many others.

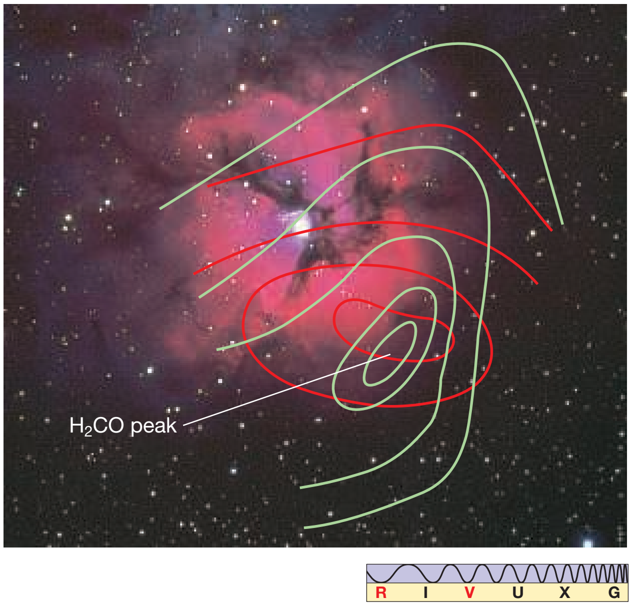
MA ANIMATION / VIDEO
Pillars Behind the Dust

MA ANIMATION / VIDEO
The Tarantula Nebula

MA ANIMATION / VIDEO
Horsehead Nebula



▲ **FIGURE 11.14 Hydrogen 21-cm Emission** A ground-state hydrogen atom switches from a higher-energy state (top) to a lower-energy state (bottom), emitting a radio photon in the process.



▲ **FIGURE 11.15 Molecules Near M20** Contour map of formaldehyde near the M20 nebula, showing how the molecule is more abundant in the darkest interstellar regions. The maximum density of formaldehyde lies just to the bottom right of the visible nebula. The colors show the intensity of formaldehyde spectral lines at two different frequencies. *(AURA)*

PROCESS OF SCIENCE CHECK

In mapping molecular clouds, why do astronomers use observations of "minority" molecules such as carbon monoxide and formaldehyde when these molecules constitute only a tiny fraction of the total in interstellar space?

▼ **FIGURE 11.16 Molecular Cloud Complexes** This false-color radio map shows the outer portion of the Milky Way as it appears in CO emission. The bright regions are molecular cloud complexes, dense regions of interstellar space where molecules abound and, apparently, stars are forming. The map is huge, extending over about a quarter of the sky. It was made from 1,696,800 observations of CO spectra. *(Five College Radio Astronomy Observatory)*

Molecular Gas

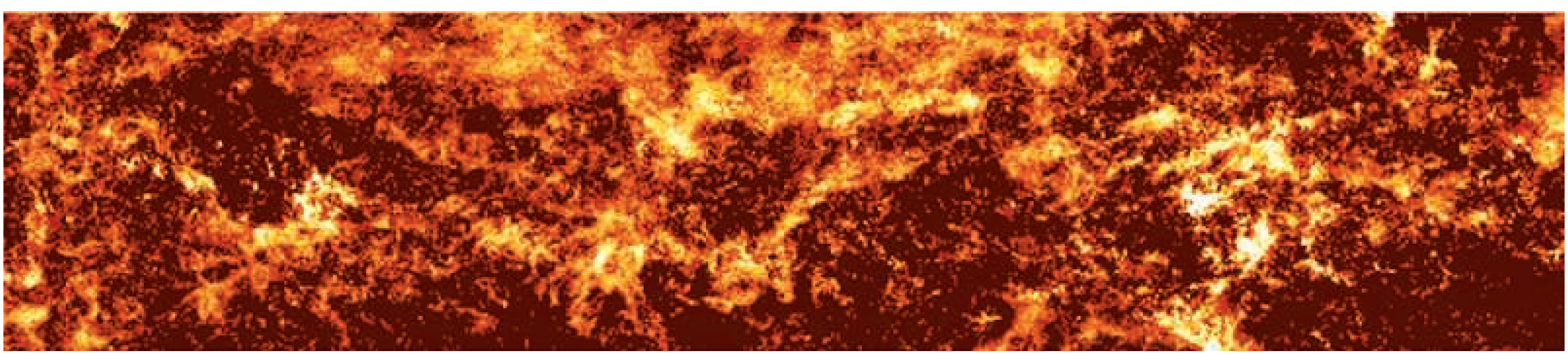
In certain interstellar regions of cold (typically 10–20 K) neutral gas, densities can reach as high as 10^{12} particles/m^3, and most gas particles are not atoms, but *molecules*. These regions are known as **molecular clouds**. Only long-wavelength radio radiation can escape from these dense, dusty parts of interstellar space.

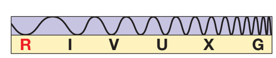
Molecular hydrogen (H_2) is by far the most common constituent of molecular clouds; but it does not emit or absorb radio radiation, so it cannot easily be used as a probe of cloud structure. Nor are 21-cm observations helpful—they are sensitive only to *atomic* hydrogen, not to the molecular form of the gas. Instead, astronomers use radio observations of "tracer" molecules, such as carbon monoxide (CO), water (H_2O), and formaldehyde (H_2CO), to study the dark interiors of these dusty regions. These molecules are produced by chemical reactions within the clouds and emit energy in the radio part of the spectrum. They are rare—perhaps one per billion hydrogen molecules—but when we observe them we can be confident that large amounts of molecular hydrogen and other important constituents are also present. Figure 11.15 shows a contour map of the distribution of formaldehyde molecules around M20. Notice that the emission peaks well away from the visible nebula.

Molecular observations reveal that the spectacular star-forming regions we see are actually parts of much larger molecular clouds. The bright emission nebula "bursts out" of its dark parent cloud when the radiation from a group of newborn stars heats and ionizes the cold molecular gas. And molecular clouds do not exist as distinct objects in space. Rather, they form huge **molecular cloud complexes** tens of parsecs across, some containing enough gas to make millions of stars like our Sun. About 1000 such complexes are known in our Galaxy. Figure 11.16 is a radio map of a large region of the sky, made using spectral lines of the CO molecule, showing molecular cloud complexes stretching across the entire field of view.

Why are molecules found only in the densest interstellar clouds? One reason is that the dust protects the fragile molecules from the harsh interstellar environment. The same absorption that prevents high-frequency radiation from getting out to our detectors also prevents it from getting in to destroy the molecules. The dust may also help form the molecules. Dust grains provide both a place where atoms can stick and react and a means of dissipating any heat associated with the reaction, which might otherwise destroy the newly formed molecules.

In recent years, astronomers have come to realize that the interstellar medium is a dynamic environment in which energy released by new-born stars (Section 11.5) and supernovae (see Chapter 12) drives large-scale, turbulent motion in the gas. The cold molecular clouds we see may simply be regions of dense gas temporarily compressed by the large-scale flow—transient islands in a sea of surrounding chaos.





11.4 Formation of Stars Like the Sun

Let us now turn our attention to the connection between the interstellar medium and the stars in our Galaxy. How do stars form? What factors determine their masses, luminosities, and spatial distribution? In short, what basic processes are responsible for the appearance of our night sky?

Gravity and Heat

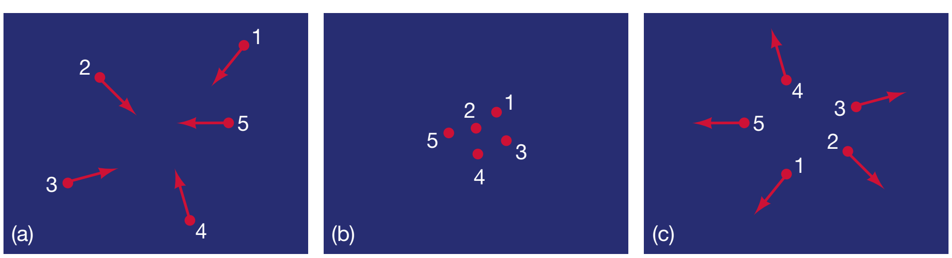
Simply stated, star formation begins when part of the interstellar medium—one of the cold, dark clouds discussed in the previous section—collapses under its own weight. An interstellar cloud is maintained in hydrostatic equilibrium by a balance between two basic opposing influences: gravity (which is always directed inward) and heat (in the form of outwardly directed pressure). ∞ ***(Sec. 9.2)*** If gravity somehow begins to dominate over heat, then the cloud can lose its equilibrium and start to contract.

Consider a small portion of a large interstellar cloud. Concentrate first on just a few atoms, as shown in Figure 11.17(a). Even though the cloud's temperature is very low, each atom has some random motion. ∞ ***(More Precisely 2-1)*** Each atom is also influenced by the gravitational attraction of all its neighbors. The gravitational force is not large, however, because the mass of each atom is so small. When a few atoms accidentally cluster for an instant, as sketched in Figure 11.17(b), their combined gravity is insufficient to bind them into a lasting, distinct clump of matter. This accidental cluster disperses as quickly as it formed (Figure 11.17c). The effect of heat—the random motion of the atoms—is much stronger than the effect of gravity.

As the number of atoms increases, their gravitational attraction increases too, and eventually the collective gravity of the clump is strong enough to prevent it from dispersing back into interstellar space. How many atoms are required for this to be the case? The answer, for a typical cool (100 K) cloud, is about 10^{57}—in other words, the clump must have mass comparable to that of the Sun. If our hypothetical clump is more massive than that, it will not disperse. Instead, its gravity will cause it to contract, ultimately to form a star.

Of course, 10^{57} atoms don't just clump together by random chance. Rather, star formation is *triggered* when a sufficiently massive pocket of gas is squeezed by some external event. Perhaps it is compressed when two blobs of gas collide, or by the shock wave produced when a nearby group of O- or B-type stars form and heat their surroundings, creating an emission nebula, or when a neighboring star explodes as a supernova (see Section 12.4). Or possibly part of an interstellar cloud simply becomes too cold for its internal pressure to support it against its own gravity. Whatever the cause, theory suggests that once the collapse begins, star formation inevitably follows.

Table 11.2 lists seven evolutionary stages that an interstellar cloud goes through before becoming a main-sequence star like our Sun. These stages are characterized by different central temperatures, surface temperatures, central densities, and radii



If more than a few atoms interact, the group would come together, start to slide by, but then pause, and finally contract into a clump.

◄ **FIGURE 11.17 Atomic Motions** The motions of a few atoms within an interstellar cloud are influenced by gravity so slightly that the atoms' paths are hardly changed (a) before, (b) during, and (c) after an accidental, random encounter.

TABLE 11.2 Prestellar Evolution of a Sun-like Star

Stage	Approximate Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (particles/m^3)	Diameter[1] (km)	Object
1	2×10^6	10	10	10^9	10^{14}	Interstellar cloud
2	3×10^4	100	10	10^{12}	10^{12}	Cloud fragment
3	10^{15}	10,000	100	10^{18}	10^{10}	Cloud fragment/protostar
4	10^6	1,000,000	3000	10^{24}	10^8	Protostar
5	10^7	5,000,000	4000	10^{28}	10^7	Protostar
6	2×10^6	10,000,000	4500	10^{31}	2×10^6	Star
7	10^{10}	15,000,000	6000	10^{32}	1.5×10^6	Main-sequence star

[1]For comparison, recall that the diameter of the Sun is 1.4×10^6 km and that of the solar system roughly 1.5×10^{10} km.

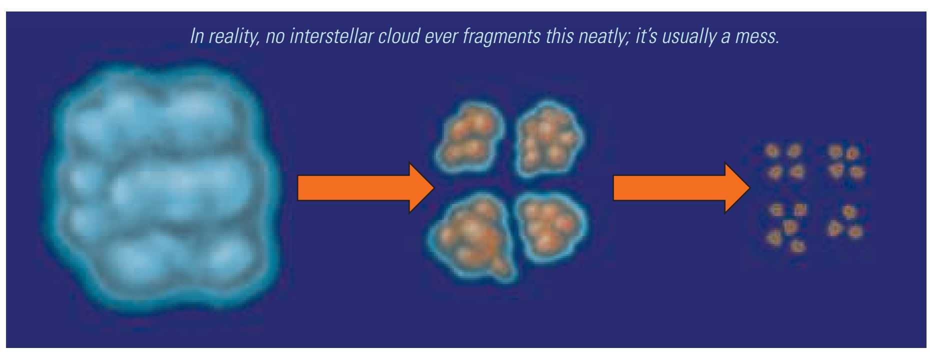
of the prestellar object. They trace its progress from a quiescent interstellar cloud to a genuine star. The numbers given in Table 11.2 and the following discussion are valid only for stars of approximately the same mass as the Sun. In the next section we will relax this restriction and consider the formation of stars of other masses.

Stage 1—An Interstellar Cloud

The first stage in the star-formation process is a dense interstellar cloud—the core of a dark dust cloud or perhaps part of a molecular cloud. These clouds are truly vast, sometimes spanning tens of parsecs (10^{14} to 10^{15} km) across. Typical temperatures are about 10 K throughout, with a density of perhaps 10^9 particles/m^3. Stage-1 clouds contain thousands of times the mass of the Sun, mainly in the form of cold atomic and molecular gas. (The dust they contain is important for cooling the cloud as it contracts and also plays a crucial role in planet formation, but it constitutes a negligible fraction of the total mass.) ∞ *(Sec. 4.3)*

The dark region outlined by the red and green radio contours in Figure 11.15 (*not* the emission nebula itself, where stars have already formed) probably represents a stage-1 cloud just starting to contract. Doppler shifts of the observed formaldehyde lines indicate that it is probably infalling. Less than a light year across, this region has a total mass over 1000 times the mass of the Sun—considerably greater than the mass of M20 itself.

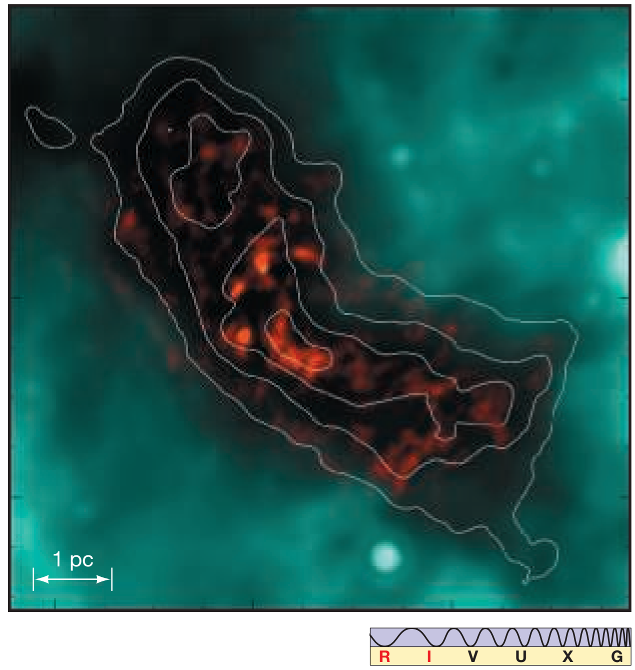
Once the cloud is compressed past the point where gravity overcomes gas pressure, theory indicates that it will naturally fragment into smaller and smaller clumps of matter due to further gravitational instabilities in the gas. As illustrated in Figure 11.18, a typical cloud may form tens, hundreds, even thousands of fragments, each destined to form a star or group of stars. The whole process, from initial unstable cloud to many collapsing fragments, takes perhaps a few hundred thousand years. Depending on the precise conditions in the cloud, it may form either a few dozen stars, each much larger than our Sun, or a collection of hundreds or thousands of stars comparable to or smaller than our Sun. There is little evidence for stars born in isolation, one star from one cloud. Most stars—perhaps



▶ **FIGURE 11.18 Cloud Fragmentation** As an interstellar cloud contracts, gravitational instabilities cause it to fragment into smaller pieces. The pieces themselves continue to fragment, eventually forming many tens or hundreds of individual stars.

all—appear to originate as members of multiple systems. Figure 11.19 presents recent observational evidence that directly supports the scenario just described. It shows a dense, dark molecular cloud near the center of our Galaxy, containing within it several dozen even denser prestellar fragments, having masses ranging from a few tens to a few hundred times the mass of the Sun.

The process of continuing fragmentation is eventually stopped by the increasing density within the shrinking cloud. As fragments continue to contract, they eventually become so dense that radiation cannot get out easily. The trapped radiation causes the temperature to rise, the pressure to increase, and the fragmentation to stop. However, the contraction continues.



▲ **FIGURE 11.19 Prestellar Fragments** This remarkable image combines infrared, millimeter, and radio observations of small molecular cloud called G0.253+0.016 near the Galactic center. The cyan image is an infrared view from *Spitzer*, while the white contours trace radio emission from molecules in the cloud, outlining its full extent. The cloud is so dense that it absorbs the infrared background, and so appears dark. The red blobs are high-resolution *ALMA* observations of dense prestellar fragments within the cloud. ∞ *(Sec. 5.4)* These fragments are well on their way to forming stars; their total mass is a few thousand times the mass of the Sun. *(J. Rathborne/Astrophysical Journal)*

Stages 2 and 3—A Contracting Cloud Fragment

As it enters stage 2, a fragment destined to form a star like the Sun—the end product of the process sketched in Figure 11.18—contains between one and two solar masses of material. Estimated to span a few hundredths of a parsec across, this fuzzy, gaseous blob is still about 100 times the size of our solar system. Its central density is about 10^{12} particles/m^3.

Even though the fragment has shrunk substantially, its average temperature is not much different from that of its parent cloud. The reason is that the gas constantly radiates large amounts of energy into space. The material of the fragment is so thin that photons produced anywhere within it easily escape without being reabsorbed, so virtually all the energy released in the contraction is radiated away and does not raise the temperature. Only at the center, where the radiation must traverse the greatest amount of material in order to escape, is there any appreciable temperature increase. The gas there might be as warm as 100 K by this stage. For the most part, however, the fragment stays cold as it shrinks.

Several tens of thousands of years after it first began contracting, the stage-2 fragment has shrunk to a gaseous sphere with a diameter roughly the size of our solar system (still 10,000 times the size of our Sun). Now, at the start of stage 3, the inner regions have become opaque to their own radiation and have started to heat up considerably, as noted in Table 11.2. The central temperature has reached about 10,000 K—hotter than the hottest steel furnace on Earth. However, the gas near the edge is still able to radiate its energy into space and so remains cool. The central density by this time is approximately 10^{18} particles/m^3 (still only 10^{-9} kg/m^3 or so).

For the first time, our fragment is beginning to resemble a star. The dense, opaque region at the center is called a **protostar.** Its mass increases as more and more material rains down on it from outside, although its radius continues to shrink because its pressure is still unable to overcome the relentless pull of gravity. By the end of stage 3, we can distinguish a "surface" on the protostar—its *photosphere*. Inside the photosphere, the protostellar material is opaque to the radiation it emits. (Note that this is the same operational definition of *surface* we used for the Sun.) ∞ *(Sec. 9.1)* From here on, the surface temperatures listed in Table 11.2 refer to the photosphere and not to the edge of the collapsing fragment, where the temperature remains low.

Figure 11.20 shows a star-forming region in Orion. Lit from within by several O-type stars, the bright Orion Nebula is partly surrounded by a vast molecular cloud that extends well beyond the roughly 1-parsec-square region bounded by the photograph in Figure 11.20(c). The Orion complex harbors several smaller sites of intense radio emission from molecules deep within its core. Shown in Figure 11.20(d), they measure about 10^{10} km, about the diameter of our solar system. Their density is about 10^{15} particles/m^3, much higher than the density of the surrounding cloud. Although the temperatures of these regions cannot be estimated reliably, many researchers regard the regions as objects between stages 2 and 3, on the threshold of becoming protostars. (See Figures 11.25 and 11.31 for visible and infrared images of part of the nebula showing other evidence for protostars.)

Stage 4—A Protostar

ANIMATION / VIDEO
Orion Nebula Mosaic

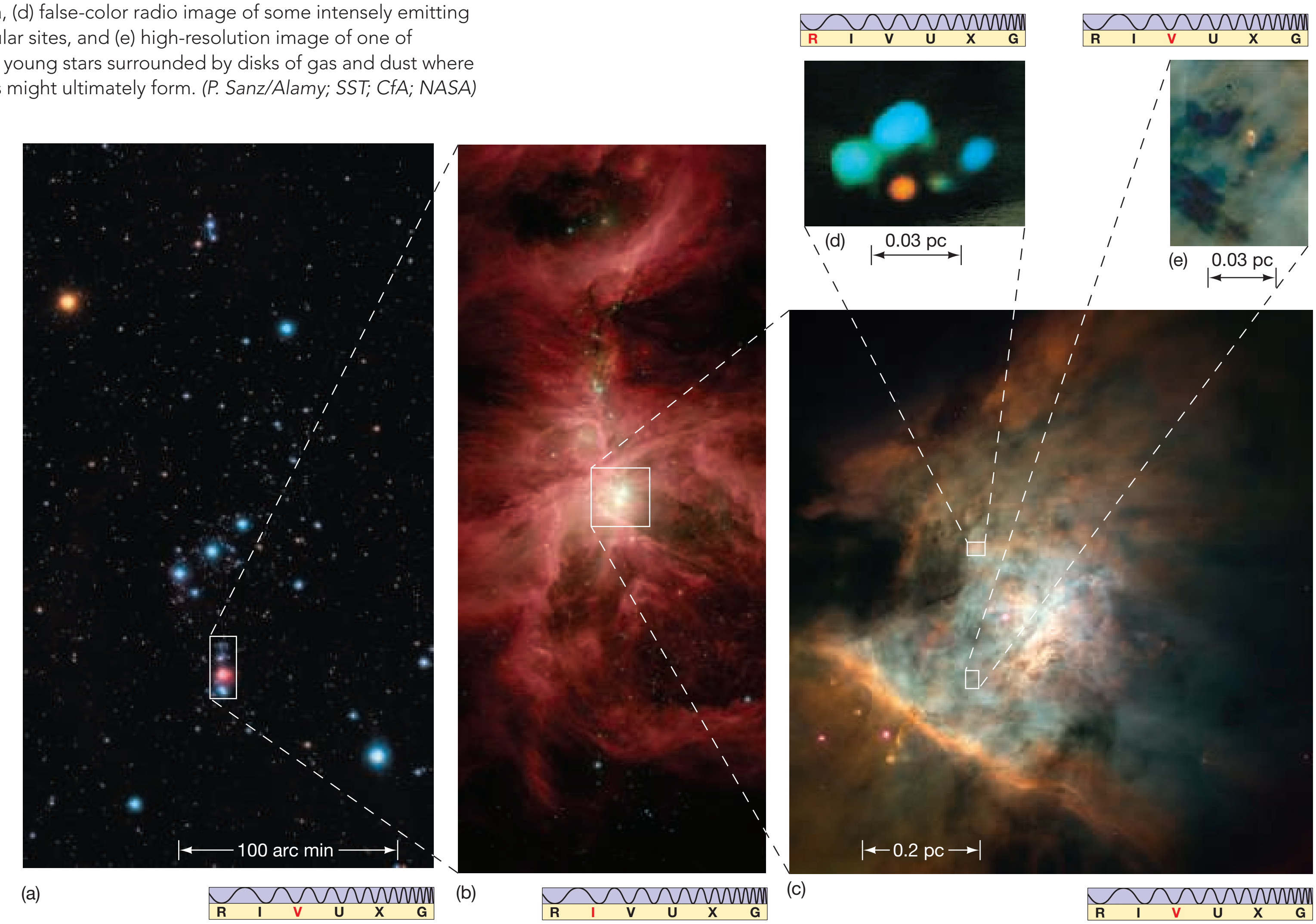
ANIMATION / VIDEO
Visit to Orion Nebula

As the protostar evolves, it shrinks, its density increases and its temperature rises, both in the core and at the photosphere. Some 100,000 years after the fragment formed, it reaches stage 4, where its center seethes at about 1,000,000 K. The electrons and protons ripped from atoms whiz around at hundreds of kilometers per second, but the temperature is still short of the 10^7 K needed to ignite the proton–proton nuclear reactions that fuse hydrogen into helium. Still much larger than the Sun, our gassy heap is now about the size of Mercury's orbit. Its surface temperature has risen to a few thousand kelvins.

Knowing the protostar's radius and surface temperature, we can calculate its luminosity using the radius–luminosity–temperature relationship. ∞ *(Sec. 10.4)* Remarkably, it turns out to be around 1000 times the luminosity of the Sun. Because nuclear reactions have not yet begun in the protostar's core, this luminosity is due entirely to the release of gravitational energy as the protostar continues to shrink and material from the surrounding fragment (which we called the solar nebula back in Chapter 4) rains down on its surface. ∞ *(Sec. 4.3)*

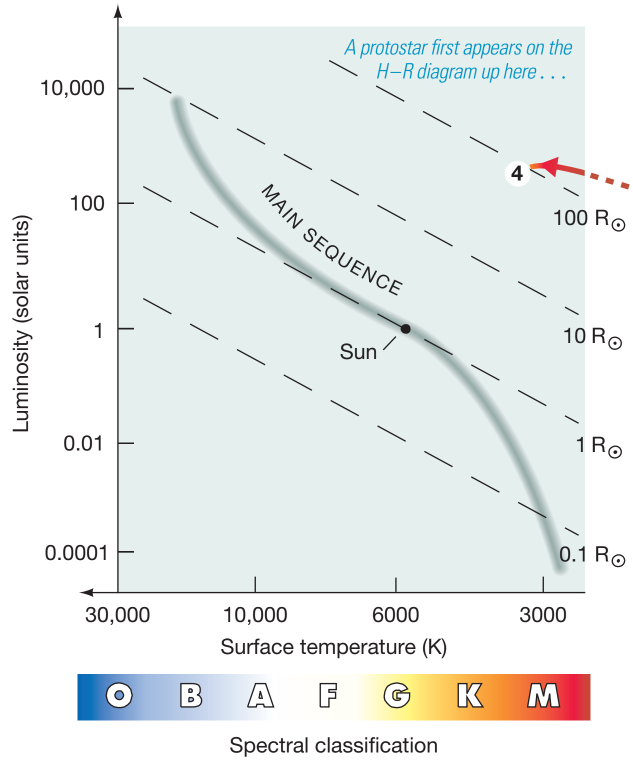
In the hunt for examples of more advanced stages of star formation, radio techniques become less useful because objects in stages 4, 5, and 6 have increasingly higher temperatures. By Wien's law, their emission shifts toward shorter wavelengths, and so they shine most strongly in the infrared. ∞ *(Sec. 2.4)* One particularly bright infrared emitter, known as the Becklin–Neugebauer object,

▼FIGURE 11.20 Orion Nebula, Up Close INTERACTIVE
(a) The constellation Orion, with the region around its famous emission nebula marked by a rectangle (see Figure 0.2). (b) Enlargement of the framed region in part (a), but here shown in the infrared, revealing how the nebula is partly surrounded by a vast molecular cloud. Various parts of this cloud are probably fragmenting and contracting, with even smaller sites forming protostars. The three frames at the right show some of the evidence for those protostars: (c) real-color visible image of embedded nebular "knots" within the Orion Nebula, (d) false-color radio image of some intensely emitting molecular sites, and (e) high-resolution image of one of several young stars surrounded by disks of gas and dust where planets might ultimately form. *(P. Sanz/Alamy; SST; CfA; NASA)*



was detected in the core of the Orion molecular cloud in the 1970s. Its luminosity is around 1000 times the luminosity of the Sun. Most astronomers agree that this warm, dense blob is a high-mass protostar, probably around stage 4.

By the time stage 4 is reached, our protostar's physical properties can be plotted on a Hertzsprung–Russell (H–R) diagram. ∞ *(Sec. 10.5)* At each phase of a star's evolution, its surface temperature and luminosity can be represented by a single point on the diagram. The motion of that point around the diagram as the star evolves is known as the star's **evolutionary track.** It is a graphical representation of a star's life. Note that it has nothing to do with any real spatial motion of the star. The red track on Figure 11.21 depicts the approximate path followed by our interstellar cloud fragment since it became a protostar at the end of stage 3 (which itself lies off the right-hand edge of the figure). Figure 11.22 is an artist's sketch of an interstellar gas cloud proceeding along the evolutionary path outlined so far.



▲ **FIGURE 11.21 Protostar on the H–R Diagram** The red arrow indicates the approximate evolutionary track followed by an interstellar cloud fragment before becoming a stage-4 protostar. The boldface numbers on this and subsequent H–R plots refer to the prestellar evolutionary stages listed in Table 11.2.

Stage 5—Protostellar Evolution

Our protostar is still not in equilibrium. Even though its temperature is now so high that outward-directed pressure has become a powerful countervailing influence against gravity's inward pull, the balance is not yet perfect. The protostar's internal heat gradually diffuses out from the hot center to the cooler surface, where it is radiated away into space. As a result, the contraction slows, but it does not stop completely.

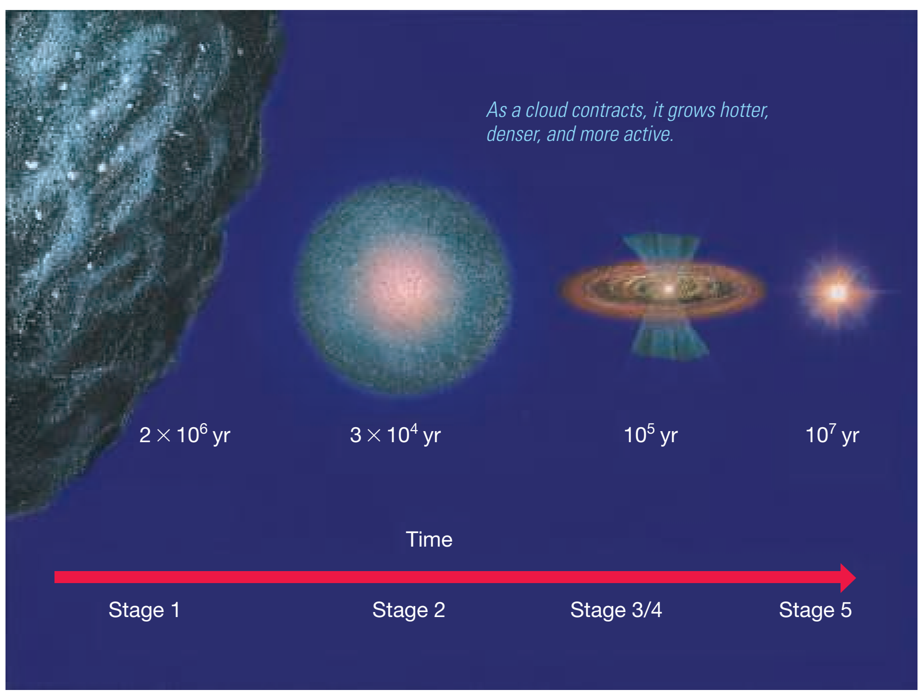
After stage 4, the protostar moves downward on the H–R diagram (toward lower luminosity) and slightly to the left (toward higher temperature), as shown in Figure 11.23. By stage 5, the protostar has shrunk to about 10 times the size of the Sun, its surface temperature is about 4000 K, and its luminosity has fallen to about 10 times the solar value. The central temperature has risen to about 5,000,000 K. The gas is completely ionized by now, but the protons still do not have enough thermal energy for nuclear fusion to begin.

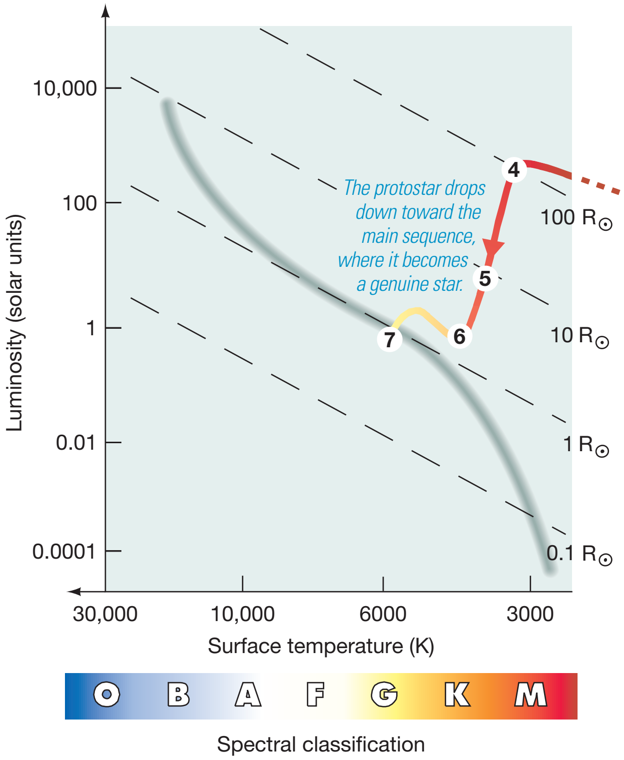
Protostars often exhibit violent surface activity during this phase of their evolution, resulting in extremely strong protostellar winds, much denser than that of our Sun. This portion of the evolutionary track is often called the **T-Tauri phase,** after T-Tauri, the first "star" (actually protostar) to be observed in this stage of prestellar development. The interaction between the strong winds and the nebular disk out of which the protostar (and possibly planets) is still forming often results in a *bipolar flow*—expelling two "jets" of matter perpendicular to the disk. Figure 11.24(a) shows a particularly striking example.

These outflows can be very energetic. Figure 11.24(b) shows a portion of the Orion molecular cloud, south of the Orion Nebula, where a protostar is seen still surrounded by a bright nebula, its turbulent wind spreading out into the interstellar medium. Below it (enlarged in the inset) are twin jets known as HH1 and HH2. (HH stands for Herbig–Haro, after the investigators who first cataloged such objects.) Formed in another (unseen) protostellar disk, these jets have traveled outward for almost half a light-year before colliding with interstellar matter. More Herbig–Haro objects can be seen in the upper right portion of the figure.

Events proceed more slowly as the protostar approaches the main sequence. The initial contraction and fragmentation of the interstellar cloud occurred quite rapidly, but by

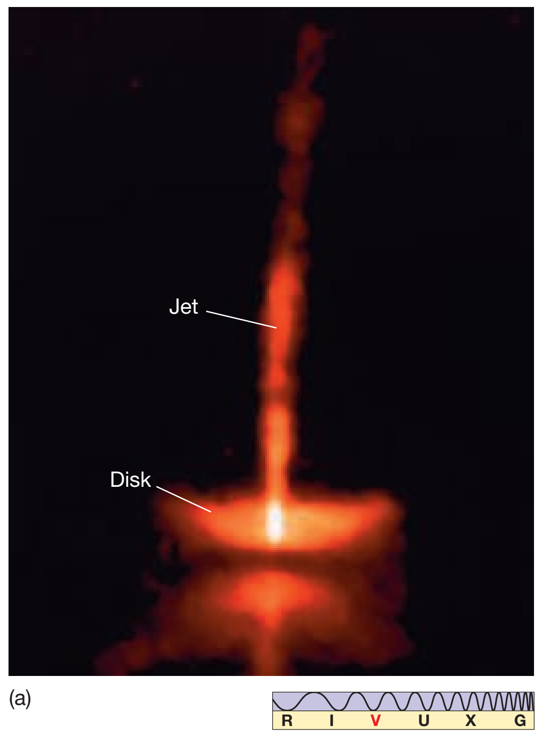
▼ **FIGURE 11.22 Interstellar Cloud Evolution** Artist's conception of the changes in an interstellar cloud during the early evolutionary stages outlined in Table 11.2. (Not drawn to scale.) The duration of each stage, in years, is indicated.





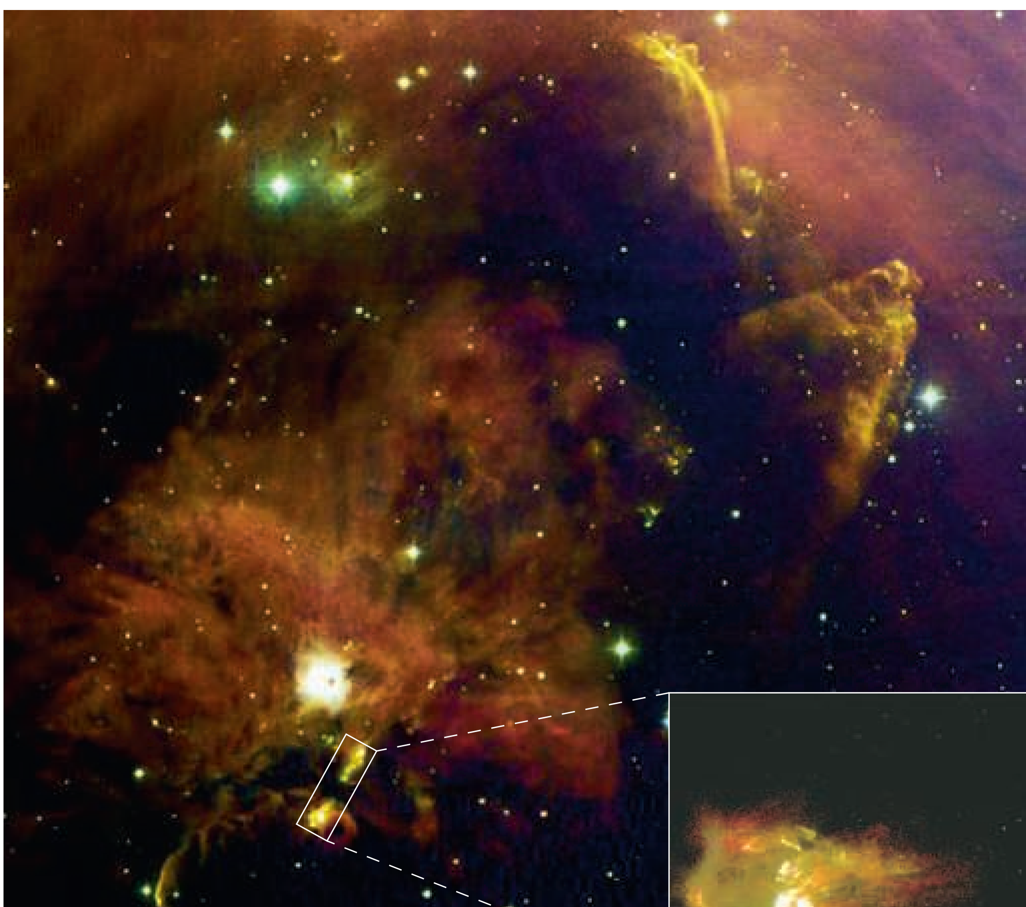
◀ **FIGURE 11.23 Newborn Star on the H–R Diagram** INTERACTIVE The changes in a protostar's observed properties are shown by the path of decreasing luminosity, from stage 4 to stage 6. At stage 7, the newborn star has arrived on the main sequence.

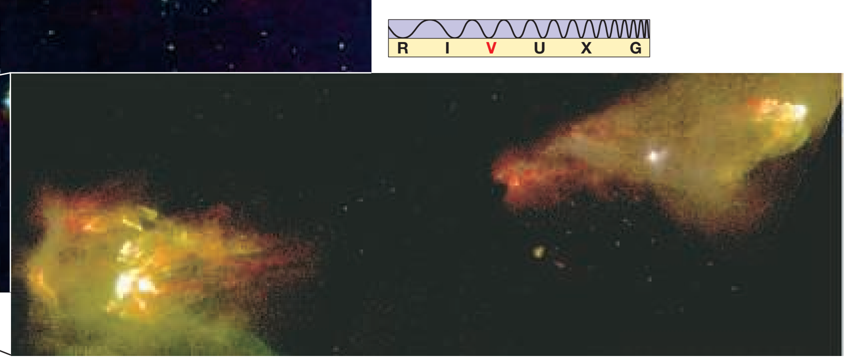
▼ **FIGURE 11.24 Protostellar Outflow** (a) This remarkable image (at right) shows two jets emanating from the young star system HH30, the result of matter accreting onto an embryonic star near the center. (b) The view below of the Orion molecular cloud shows the outflow from a newborn star, still surrounded by nebular gas. The inset shows a pair of jets called HH1/HH2, formed when matter falling onto another protostar (still obscured by the dusty cloud fragment from which it formed) creates a pair of high-speed jets of gas perpendicular to the flattened protostellar disk. The jets are nearly 1 light-year across. Several more Herbig–Haro objects can be seen at top right—one of them resembling a "waterfall." *(AURA; NASA)*



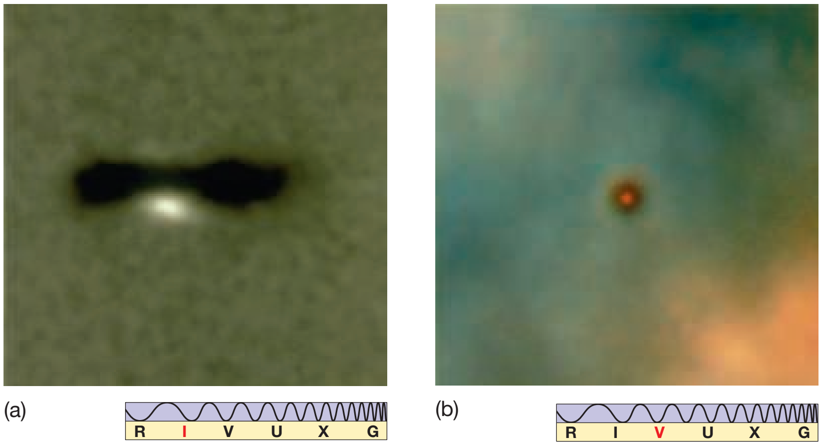
(a)

MA ANIMATION / VIDEO
Bi-Polar Outflow





(b)



◄ **FIGURE 11.25 Protostars** (a) An infrared, edge-on image of a planetary system–size dusty disk in the Orion region, showing heat and light emerging from its center. This unnamed source seems to be a low-mass protostar around stage 5 in the H–R diagram. (b) An optical, face-on image of a slightly more advanced circumstellar disk surrounding an embedded protostar in Orion. *(NASA)*

stage 5, as the protostar nears the status of a full-fledged star, its evolution slows. Its contraction is governed largely by the rate at which it can radiate its internal energy into space. As the luminosity decreases, so, too, does the contraction rate.

Until the *Infrared Astronomy Satellite (IRAS)* was launched in the early 1980s, astronomers were aware only of very massive stars forming in clouds far away. But *IRAS* showed that stars are forming much closer to home, and some of these protostars have masses comparable to that of our Sun. Figure 11.25 shows two examples of low-mass protostars—both spotted by the *Hubble Space Telescope* in a rich star-forming region in Orion. Their infrared heat signatures are those expected of a stage-5 object.

Stages 6 and 7—A Newborn Star

Some 10 million years after reaching stage 4, the protostar finally becomes a true star. By stage 6, when our roughly one-solar-mass object has shrunk to a radius of about 1,000,000 km, the contraction has raised the central temperature to 10,000,000 K—enough to ignite nuclear burning. Protons begin fusing into helium nuclei in the core, and a star is born. As shown in Figure 11.23, the star's surface temperature at this point is about 4500 K, still a little cooler than the Sun. Even though the radius of the newly formed star is slightly larger than that of the Sun, its lower temperature means that its luminosity is slightly less than (actually, about two-thirds of) the present solar value.

Indirect evidence for stage-6 stars comes from infrared observations of objects that seem to be luminous hot stars hidden from optical view by surrounding dark clouds. Their radiation is mostly absorbed by a "cocoon" of dust, then reemitted by the dust as infrared radiation. Two considerations support the idea that the hot stars responsible for heating the clouds have only recently ignited: (1) dust cocoons are predicted to disperse quite rapidly once their central stars form, and (2) these objects are invariably found in the dense cores of molecular clouds, consistent with the star-formation sequence just outlined.

Over the next 30 million years or so, the stage-6 star contracts a little more. Its central density rises to about 10^{32} particles/m^3 (more conveniently expressed as 10^5 kg/m^3), the central temperature increases to 15,000,000 K, and the surface temperature reaches 6000 K. By stage 7 the star finally reaches the main sequence just about where our Sun now resides. Pressure and gravity are finally balanced in the stellar interior, and the rate at which nuclear energy is generated in the core exactly matches the rate at which energy is radiated from the surface.

The journey from interstellar cloud to star occurs over the course of 40–50 million years. Although this is a long time by human standards, it is still less than 1 percent of the Sun's lifetime on the main sequence. Once an object begins fusing hydrogen and establishes a "gravity-in/pressure-out" hydrostatic equilibrium,

CONCEPT CHECK

What distinguishes a collapsing cloud from a protostar, and a protostar from a star?

it burns steadily for a very long time. The star's location on the H–R diagram—that is, its surface temperature and luminosity—will remain almost unchanged for the next 10 billion years.

11.5 Stars of Other Masses

The numerical values and evolutionary track just described are valid only for 1-solar-mass stars. The temperatures, densities, and radii of prestellar objects of other masses exhibit similar trends, but the details differ, in some cases quite considerably. Perhaps not surprisingly, the most massive fragments formed within interstellar clouds tend to produce the most massive protostars and eventually the most massive stars. Similarly, low-mass fragments give rise to low-mass stars.

The Zero-Age Main Sequence

Figure 11.26 compares the theoretical pre-main-sequence evolutionary track taken by our Sun with the corresponding tracks of a 0.3-solar-mass star and a 3.0-solar-mass star. All three tracks traverse the H–R diagram in the same general manner, but cloud fragments that eventually form stars more massive than the Sun approach the main sequence along a higher track on the diagram, while those destined to form less massive stars take a lower track. The *time* required for an interstellar cloud to become a main-sequence star also depends strongly on its mass. ∞ *(Sec. 10.7)* The most massive fragments contract into O-type stars in a mere million years, roughly 1/50 the time taken by the Sun. The opposite is the case for prestellar objects having masses much less than our Sun. A typical M-type star, for example, requires nearly a billion years to form.

Whatever the mass, the endpoint of the prestellar evolutionary track is the main sequence. A star is considered to have reached the main sequence when hydrogen burning begins in its core and the star's properties settle down to stable values. The main-sequence band predicted by theory is usually called the **zero-age main sequence** (ZAMS). It agrees quite well with the main sequences observed for stars in the vicinity of the Sun and those observed in more distant stellar systems.

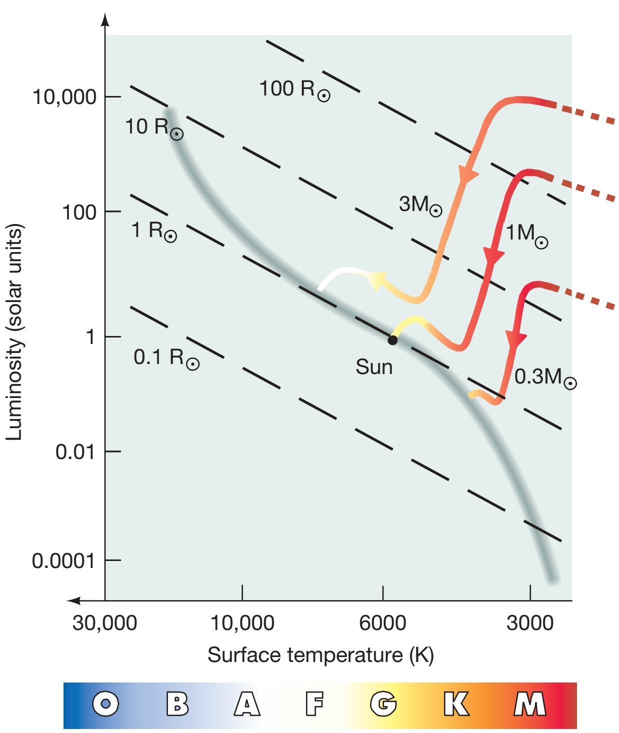
It is important to realize that *the main sequence is not an evolutionary track—stars do not evolve along it*. Rather, it is a "waystation" on the H–R diagram where stars stop and spend most of their lives—low-mass stars at the bottom, high-mass stars at the top. Once on the main sequence, a star stays in roughly the same location in the H–R diagram during its whole time as a stage-7 object. In other words, a star that arrives on the main sequence as, say, a G-type star can never "work its way up" to become a B- or an O-type main-sequence star, nor move down to become an M-type red dwarf. As we will see in Chapter 12, the next stage of stellar evolution occurs when a star leaves the main sequence. When this occurs, the star will have pretty much the same surface temperature and luminosity it had when it arrived on the main sequence millions (or billions) of years earlier.

"Failed" Stars

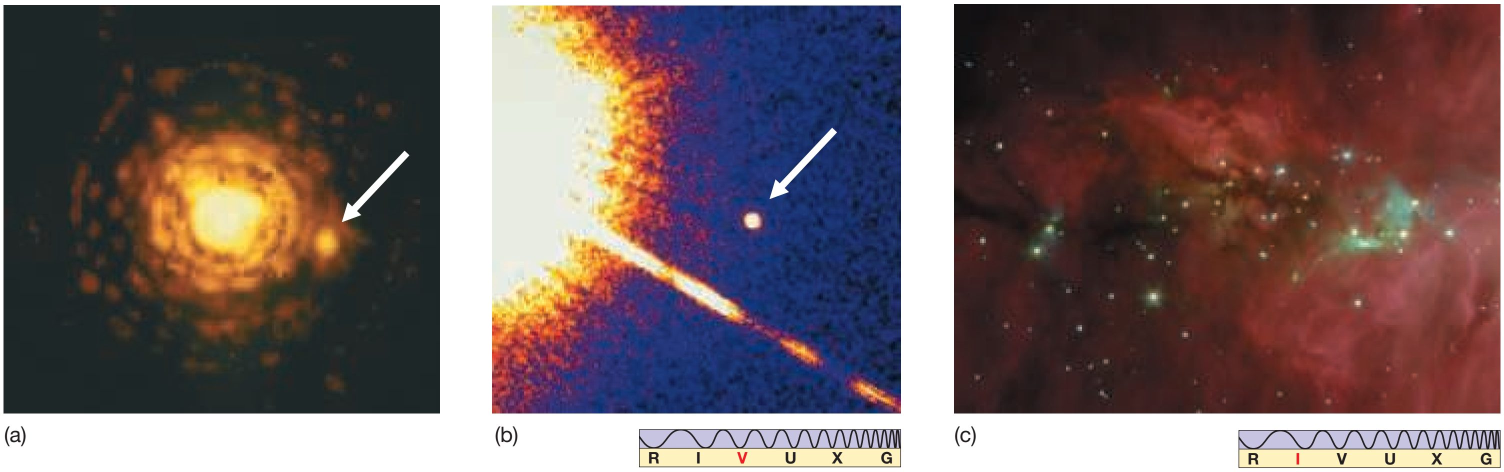
Some cloud fragments are too small ever to become stars. Pressure and gravity come into equilibrium before the central temperature becomes hot enough to fuse hydrogen, so they never evolve beyond the protostar stage. Rather than turning into stars, such low-mass fragments continue to cool, eventually becoming compact, dark "clinkers"—cold fragments of unburned matter—in interstellar space. Small, faint, and cool (and growing ever colder), these objects are known collectively as **brown dwarfs.** On the basis of theoretical modeling, astronomers calculate that the minimum mass of gas needed to generate core temperatures high enough to begin nuclear fusion is about 0.08 solar masses—80 times the mass of Jupiter.

CONCEPT CHECK

Do stars evolve along the main sequence?

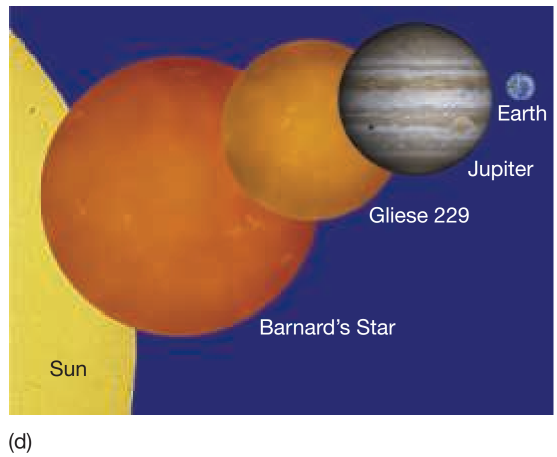


▲ **FIGURE 11.26 Prestellar Evolutionary Tracks** Prestellar evolutionary paths for stars more massive and less massive than our Sun.



Vast numbers of brown dwarfs may well be scattered throughout the universe—fragments frozen in time somewhere in the cloud-contraction phase. With our current technology, we have great difficulty in detecting them, whether they orbit other stars or float alone in space. We can telescopically detect stars and spectroscopically infer atoms and molecules, but low-mass astronomical objects far beyond our solar system are very hard to see. However, recent advances in observational hardware and image-processing techniques have identified many likely brown dwarf candidates, often using techniques similar to those employed in the search for extrasolar planets. *(Sec. 4.4)* (Recall that most stars are found in binaries; the same may very well be true of brown dwarfs. *(Sec. 10.7)*)

Figure 11.27 shows Gliese 623, a binary system containing a brown dwarf candidate, originally identified by radial velocity measurements and Gliese 229, first identified as a possible brown dwarf by ground-based infrared observations. More recent infrared images from space show many more brown dwarf candidates. Figure 11.27(c) is a *Spitzer* image of a small star cluster showing not only many bright stars, but also numerous much fainter objects thought to be brown dwarfs. Based on current observations, it seems that up to 100 billion cold, dark, brown dwarfs may lurk in the depths of interstellar space—comparable to the total number of "real" stars in our Galaxy. Figure 11.27(d) compares brown dwarfs, notably Gleise 229 of part (b), to some other well-known objects.



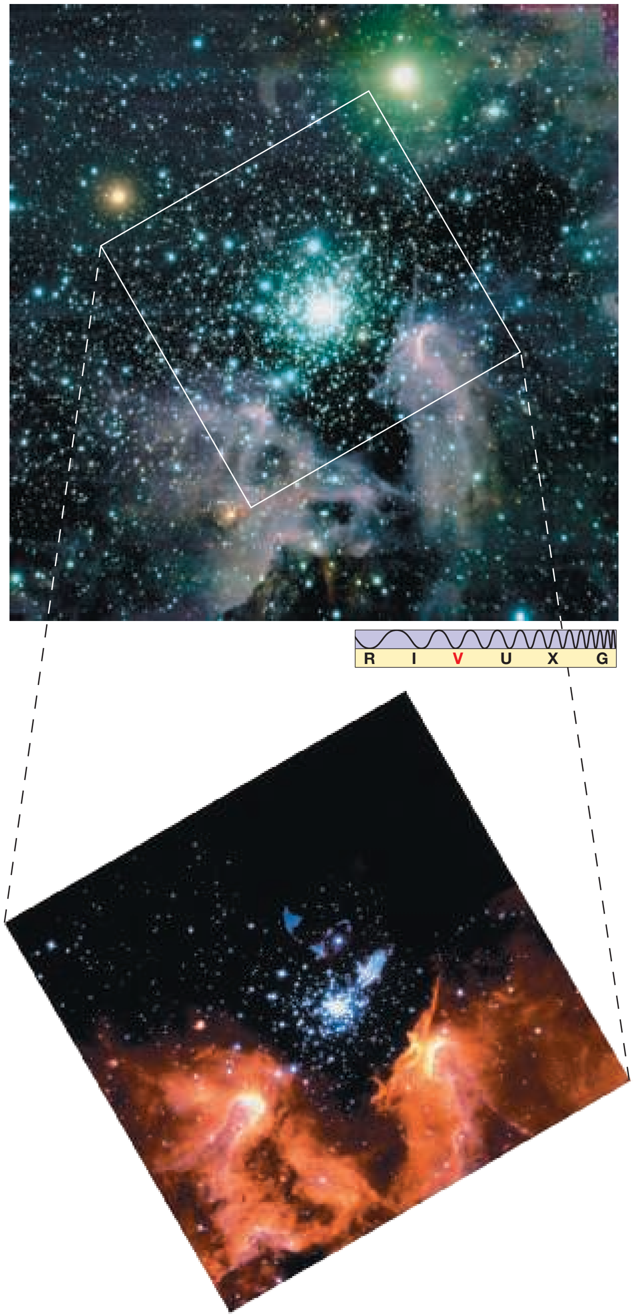
▲ **FIGURE 11.27 Brown Dwarfs** (a) This image shows Gliese 623, a binary system that may contain a brown dwarf (marked by an arrow). (b) This image of the binary-star system Gliese 229 shows two objects only 7" apart; the fainter "star" (arrow) has a luminosity only a few millionths that of the Sun and an estimated mass about 50 times that of Jupiter. (The rings in part a and the spike in part b are instrumental artifacts.) (c) An infrared image of a star cluster just north of the Orion Nebula, showing bright objects that are stars and many faint specks that are brown-dwarf candidates. (d) This rendering compares the sizes of some stars, brown dwarfs, and planets. *(NASA)*

11.6 Star Clusters

The end result of the contraction and fragmentation of an interstellar gas cloud is a group of stars, all formed from the same parent cloud and lying in the same region of space. Such a collection of stars is called a **star cluster.** Figure 11.28 shows a spectacular view of a newborn star cluster and (part of) the interstellar cloud from which it came. Because all the stars formed at the same time out of the same cloud and under the same environmental conditions, clusters in many cases are near-ideal "laboratories" for stellar studies—not in the sense that astronomers can perform experiments on them, but because the properties of the stars are very tightly constrained. The only factor distinguishing one star from another in the same cluster is mass, so theoretical models of star formation and evolution can be compared with reality without the complications introduced by broad spreads in age, chemical composition, and place of origin.

Clusters and Associations

Figure 11.29(a) shows a small star cluster called the Pleiades, or Seven Sisters, a well-known naked-eye object in the constellation Taurus, lying about 120 pc from Earth. This type of loose, irregular cluster, found mainly in the plane of the Milky



▲ **FIGURE 11.28 Newborn Cluster** The star cluster NGC 3603 and part of the larger molecular cloud in which it formed. The cluster contains about 2000 bright stars and lies some 6000 pc from Earth. The field of view shown here spans about 20 light-years. Radiation from the cluster has cleared a cavity in the cloud several light-years across. The inset shows the central area more clearly, revealing many small stars less massive than the Sun. *(ESO; NASA)*

ANIMATION / VIDEO
Carina Nebula

Way, is called an **open cluster.** Open clusters typically contain from a few hundred to a few tens of thousands of stars and are a few parsecs across. Figure 11.29(b) shows the H–R diagram for stars in the Pleiades. The cluster contains stars in all parts of the main sequence. The blue stars must be relatively young, for, as we saw in Chapter 10, they burn their fuel very rapidly. ∞ *(Sec. 10.7)* Thus, even though we have no direct evidence of the cluster's birth, we can estimate its age at less than 20 million years, the lifetime of an O-type star. The wisps of leftover gas evident in the photograph are further evidence of the cluster's youth.

Less massive, but more extended, clusters are known as **associations.** These typically contain no more than a few hundred stars, but may span many tens of parsecs. Associations tend to be rich in very young stars and are very loosely bound—if they are bound at all. Many associations appear to be expanding freely into space and dissolving following their formation.

Figure 11.30(a) shows a very different type of star cluster, called a **globular cluster.** All globular clusters are roughly spherical (which accounts for their name), are generally found away from the Milky Way plane, and contain hundreds of thousands, and sometimes millions, of stars spread out over about 50 pc. The H–R diagram for this cluster (called Omega Centauri) is shown in Figure 11.30(b).

The most outstanding feature of globular clusters is their lack of upper main-sequence stars. In fact, globular clusters contain no main-sequence stars with masses greater than about 0.8 times the mass of the Sun. (The A-type stars in this plot are stars at a much later evolutionary stage that happen to be passing through the location of the upper main sequence.) Their more massive O- through F-type stars have long since exhausted their nuclear fuel and disappeared from the main sequence. On the basis of these and other observations, astronomers estimate that all globular clusters are at least 10 billion years old. They contain the oldest known stars in our Galaxy. Astronomers speculate that the 150 or so globular clusters observed today are just the survivors of a much larger population of clusters that formed long ago.

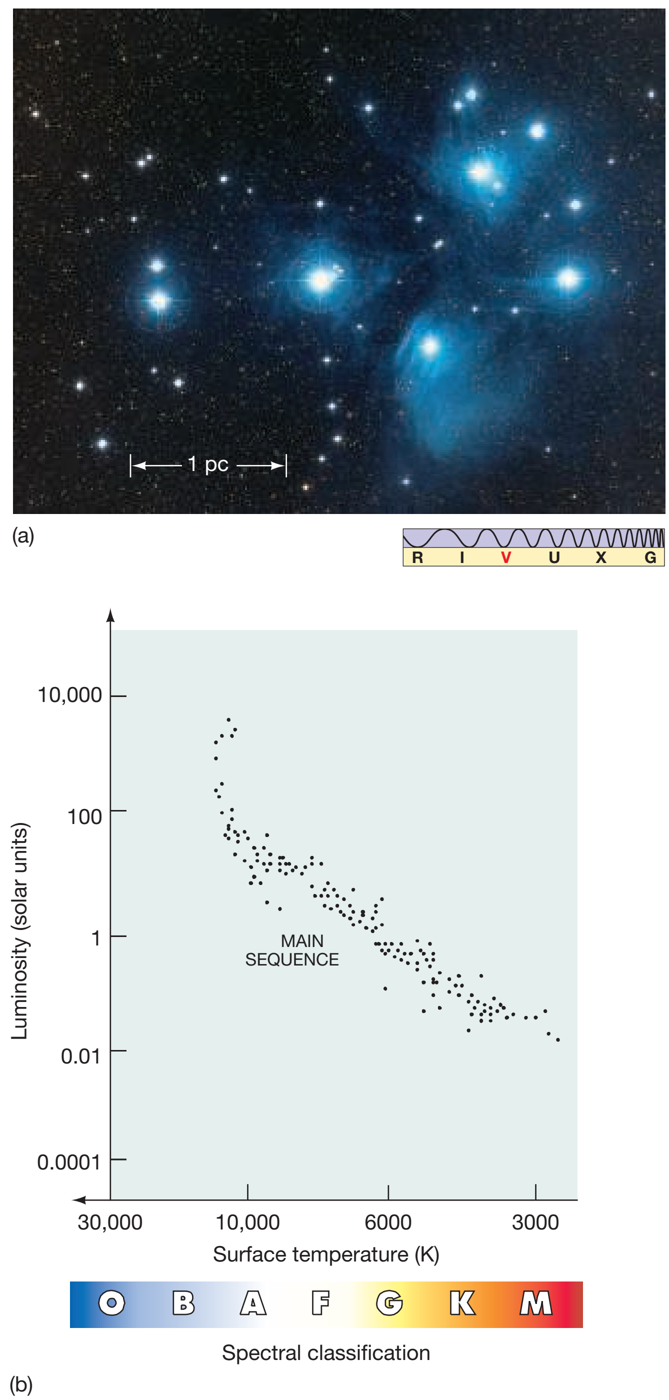
Clusters and Nebulae

How many stars form in a cluster, and of what type are they? What does the collapsed cloud look like once star formation has run its course? At present, although the main stages (3–7) in the formation of individual stars are fairly well established, the answers to these broader questions (involving stages 1 and 2) remain sketchy. Low-mass stars are much more common than high-mass ones, but an explanation of exactly why this is so still awaits a more thorough understanding of the star-formation process. ∞ *(Sec. 10.7)*

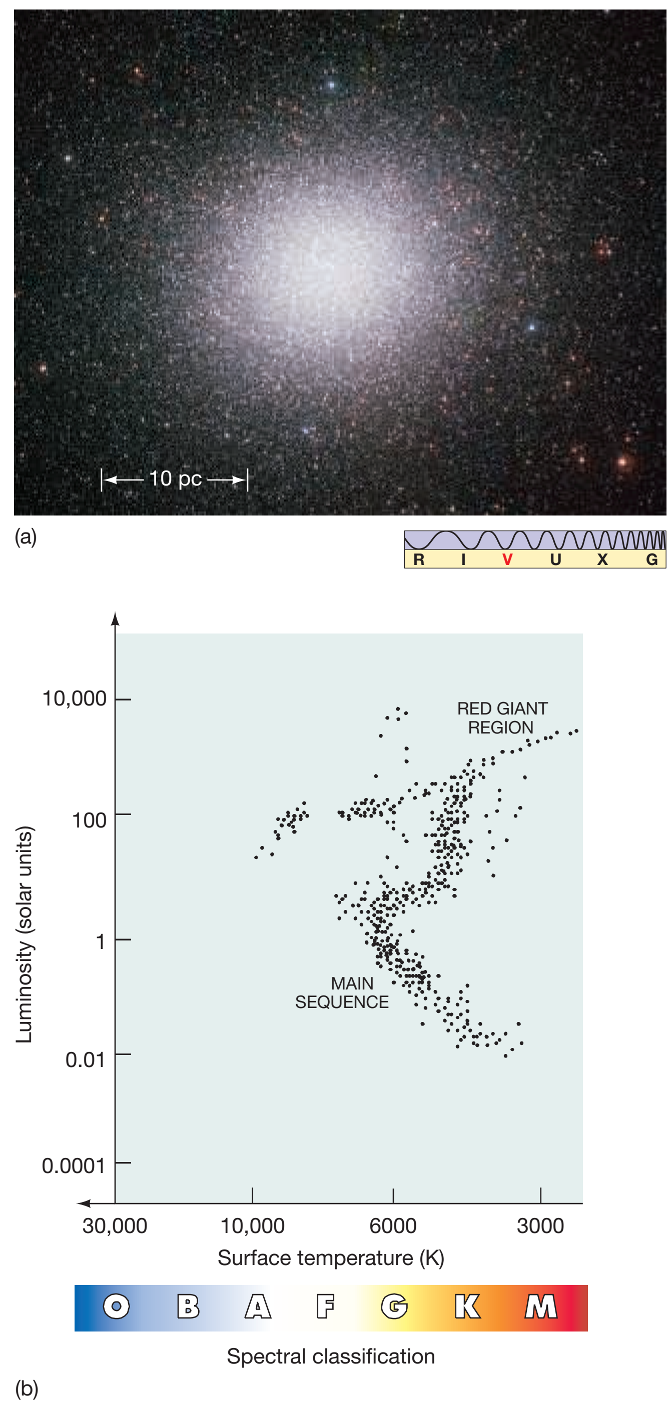
At present, researchers are divided on whether more massive stars simply form from denser or more massive clumps of interstellar gas or whether all stars form as relatively lightweight objects (with masses much less than the mass of the Sun). Stars subsequently grow by accretion from their surroundings, in a manner reminiscent of the growth of planetesimals in the early solar system. ∞ *(Sec. 4.3)* In the latter view, the most massive stars are the ones that win the competition for resources.

In either case, computer simulations of star-forming clouds (see Figure 11.31) suggest that the sequence of events leading to main-sequence stars may be strongly influenced by physical interactions—close encounters and even collisions—between protostars within the cluster. The simulations indicate that the strong gravitational fields of the most massive protostars give them a competitive advantage over their smaller rivals in attracting gas from the surrounding nebula, causing giant protostars to grow even faster. Close encounters with massive protostars also tend to disrupt smaller protostellar disks, terminating the growth of their central protostars and ejecting planets and low-mass brown dwarfs from the disk into intracluster space. In dense clusters these interactions may even lead to mergers and further growth of massive objects.

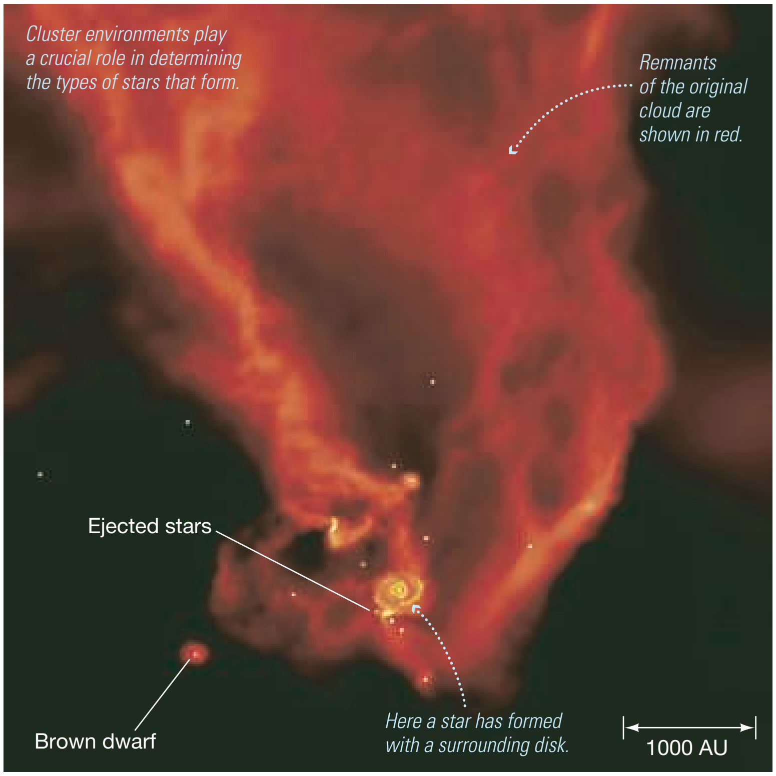
Thus, even though many details remain to be filled in, we can see several ways in which the cluster environment affects the kinds of stars that form there. The most massive stars form fastest and in the process tend to prevent the formation of more high-mass stars, both by stealing their raw material and by helping destroy their disks. Eventually, the intense radiation from newborn O and B stars disrupts the environment in which lower-mass stars are forming, "freezing in" their masses. This also helps explain the existence of brown dwarfs by providing a mechanism whereby star formation can stop before nuclear fusion begins in a low-mass stellar core.



▲ **FIGURE 11.29 Open Cluster** (a) The Pleiades cluster (also known as the Seven Sisters because only six or seven of its stars can be seen with the naked eye) lies about 120 pc from the Sun. (b) An H–R diagram for all the stars of this well-known open cluster. *(NOAO)*



▲ **FIGURE 11.30 Globular Cluster** (a) The globular cluster Omega Centauri is approximately 5000 pc from Earth and some 40 pc in diameter. (b) An H–R diagram for some of its stars. *(P. Seitzer)*

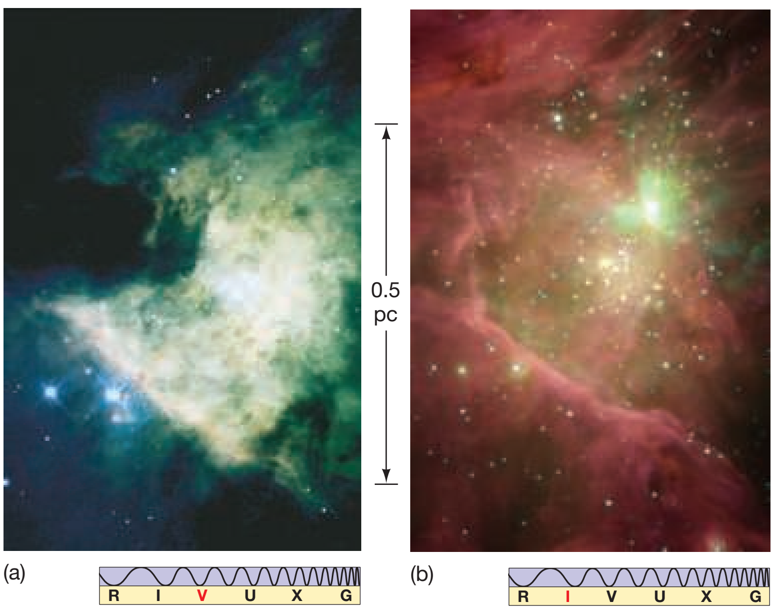


◀ **FIGURE 11.31 Protostellar Collisions** INTERACTIVE In the congested environment of a young cluster, star formation is a competitive and violent process. Large protostars may grow by "stealing" gas from smaller ones, and the extended disks surrounding most protostars can lead to collisions and even mergers. This frame from a supercomputer simulation shows a small star cluster emerging from an interstellar cloud that originally contained some 50 solar masses of material spread over a volume 1 light-year across. *(M. Bate, I. Bonnell, and V. Bromm)*

Young star clusters are often shrouded in gas and dust, making them hard to see in visible light, but infrared observations clearly demonstrate that clusters really are found within star-forming regions. Figure 11.32 compares optical (a) and infrared (b) views of the central regions of the Orion Nebula. The optical image shows the Trapezium, the group of four bright stars responsible for ionizing the nebula; the infrared image reveals an extensive cluster of stars within and behind the visible nebula and shows many stages of star formation, including nearly 1000 new stars forming and interacting with the surrounding cloud.

Eventually, star clusters dissolve into individual stars. In some cases, the irregular star formation process illustrated in Figure 11.31 simply leaves the newborn cluster gravitationally unbound. In others, the ejection of leftover gas reduces the cluster's mass so much that it becomes unbound and quickly disperses. The tidal gravitational field of the Galaxy slowly destroys the remainder. ∞ *(Sec. 5.2)* The most massive systems—the globular clusters—may survive for billions of years, but most clusters surrender their stars to the Galactic population in less than a few hundred million years.

Take another look at the sky one clear, dark evening. Ponder all of the cosmic activity you have learned about as you peer upward at the stars. After studying this chapter, you may find that you have to modify your view of the night sky. Even the seemingly quiet nighttime darkness is dominated by continual change.



◀ **FIGURE 11.32 Young Stars in Orion** INTERACTIVE (a) Visible *Hubble* and (b) infrared *Spitzer* views of the central part of the Orion Nebula. The visible image is dominated by the emission nebula and shows few stars. However, the infrared image shows an extensive star cluster containing stars of many masses, possibly including many brown dwarfs (see also Figures 3.24c and d). *(NASA)*

CONCEPT CHECK

If stars in a cluster all start to form at the same time, how can some influence the formation of others?

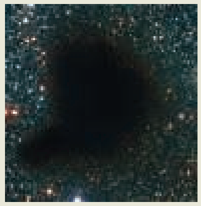
THE BIG QUESTION

When did the first stars form? We observe stars forming today throughout the Milky Way and myriad other galaxies, and studies of distant stars imply that they formed even more efficiently billions of years ago. Astronomers are pushing back the veil of ancient star formation, trying to understand how and when conditions in the early universe first allowed gas without walls—stars—to ignite as brilliant balls of fire.

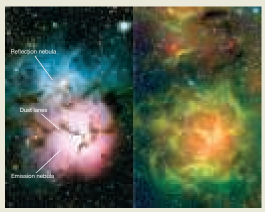
CHAPTER REVIEW

SUMMARY

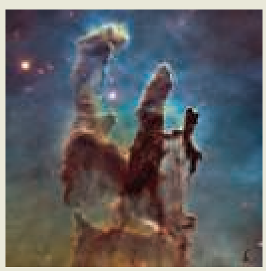
LO1 The **interstellar medium** (p. 304) occupies the space between stars. It is composed of cold (less than 100 K) gas, mostly atomic or molecular hydrogen and helium, and **dust grains** (p. 305) containing carbon, silicates, and iron. Interstellar dust is very effective at blocking our view of distant stars, even though the density of the interstellar medium is very low. The spatial distribution of interstellar matter is very patchy. The dust preferentially absorbs short-wavelength radiation, leading to **reddening** (p. 305) of light passing through interstellar clouds.



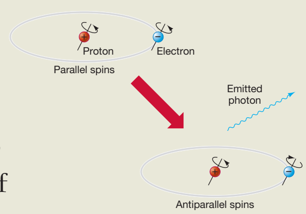
LO2 **Emission nebulae** (p. 308) are extended clouds of hot, glowing interstellar matter. Those associated with star formation are caused by hot O- and B-type stars heating and ionizing their surroundings. They are often crossed by dark **dust lanes** (p. 309)—part of the larger molecular cloud from which they formed.



LO3 **Dark dust clouds** (p. 311) are cold, irregularly shaped regions in the interstellar medium that diminish or completely obscure the light from background stars. The interstellar medium also contains many cold, dark **molecular clouds** (p. 314). Dust within these clouds probably both protects the molecules and acts as a catalyst to help them form. Molecular clouds are likely sites of future star formation. Often, several molecular clouds are found close to one another, forming a **molecular cloud complex** (p. 314) millions of times more massive than the Sun.

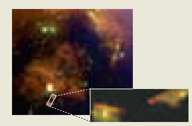


LO4 Astronomers can study dark interstellar clouds by observing their effect on the light from more distant stars. Another way to observe these regions of interstellar space is through spectral analysis of the **21-centimeter line** (p. 313) produced whenever the electron in a hydrogen atom reverses its spin, changing its energy very slightly in the process. Astronomers usually study these clouds through observations of other molecules that are less common than hydrogen but much easier to detect.

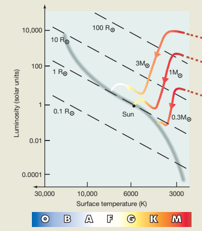


LO5 Stars form when an interstellar cloud collapses under its own gravity and breaks up into smaller pieces. The evolution of the contracting cloud can be represented as an **evolutionary track** (p. 319) on the Hertzsprung–Russell diagram. A cold interstellar cloud (stage 1) containing a few thousand solar masses of gas can fragment into tens or hundreds of smaller clumps of matter, from which stars eventually form. As a collapsing prestellar fragment heats up and becomes denser (stages 2 and 3), it eventually becomes a **protostar** (stage 4; p. 317)—a warm, very luminous object that emits radiation mainly in the infrared portion of the electromagnetic spectrum. The protostar contracts as it radiates its internal energy into space (stage 5). Eventually, the central temperature becomes high enough for hydrogen fusion to begin (stage 6), and the protostar becomes a star (stage 7).

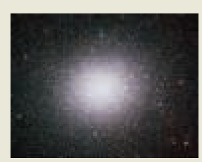
LO6 Dark dust clouds and globules are examples of stage-1 clouds and stage-2 collapsing fragments. Examples of stage-3 objects have been observed in some star-forming regions, such as Orion. Stars in the **T-Tauri phase** (p. 319) are examples of stage-4/5 protostars. Low-mass stage-6 stars on their final approach to the main sequence are found in star-forming regions.



LO7 Stars of different masses go through similar formation stages, but end up at different locations along the main sequence, high-mass stars at the top, low-mass stars at the bottom. The **zero-age main sequence** (p. 322) is the main sequence predicted by stellar evolutionary theory. It agrees very well with observed main sequences. The most massive stars have the shortest formation times and the shortest main-sequence lifetimes. At the other extreme, some low-mass fragments never reach the point of nuclear ignition. Objects not massive enough to fuse hydrogen to helium are called **brown dwarfs** (p. 322). They may be very common in the universe.



LO8 A single contracting and fragmenting cloud can give rise to hundreds or thousands of stars—a **star cluster** (p. 323). **Open clusters** (p. 324), which are loose, irregular clusters that typically contain from a few tens to a few thousands of stars, are found mostly in



the Milky Way plane. They typically contain many bright blue stars, indicating that they formed relatively recently. **Globular clusters** (p. 324) are roughly spherical and may contain millions of stars. They include no main-sequence stars more massive than the Sun, indicating that they formed long ago. Infrared observations have revealed young star clusters within several emission nebulae. Eventually, star clusters break up into individual stars, although the process may take billions of years to complete.

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Problems labeled POS explore the process of science. VIS problems focus on reading and interpreting visual information. LO connects to the introduction's numbered Learning Outcomes.

REVIEW AND DISCUSSION

1. LO1 What is the composition of interstellar gas? Of interstellar dust?
2. LO3 How is interstellar matter distributed through space?
3. What are some methods that astronomers use to study interstellar dust?
4. LO2 What is an emission nebula?
5. LO4 What is 21-centimeter radiation, and why is it useful to astronomers?
6. If our Sun were surrounded by a cloud of gas, would this cloud be an emission nebula? Why or why not?
7. LO5 Briefly describe the basic chain of events leading to the formation of a star like the Sun.
8. What is an evolutionary track?
9. Why do stars tend to form in groups?
10. What critical event must occur in order for a protostar to become a star?
11. LO7 What are brown dwarfs?
12. POS Stars live much longer than we do, so how do astronomers test the accuracy of theories of star formation?
13. LO6 At what evolutionary stages must astronomers use radio and infrared radiation to study prestellar objects? Why can't they use visible light?
14. POS Explain the usefulness of the H–R diagram in studying the evolution of stars. Why can't evolutionary stages 1–3 be plotted on the diagram?
15. LO8 Compare and contrast the properties of open and globular star clusters.

CONCEPTUAL SELF-TEST: TRUE OR FALSE? / MULTIPLE CHOICE

1. Interstellar matter is quite evenly distributed throughout the Milky Way Galaxy. (T/F)
2. Emission nebulae radiate mainly in the ultraviolet part of the electromagnetic spectrum. (T/F)
3. Twenty-one-centimeter radiation can be used to probe the interiors of molecular clouds. (T/F)
4. More massive stars form more rapidly. (T/F)
5. Brown dwarfs take a long time to form, but will eventually become visible as stars on the lower main sequence. (T/F)
6. The formation of the first high-mass stars in a collapsing cloud tends to inhibit further star formation within that cloud. (T/F)
7. Most stars form as members of groups or clusters. (T/F)
8. VIS The dark interstellar globule shown in Figure 11.2(b) is about the same size as (a) a cloud in Earth's atmosphere; (b) the entire planet Earth; (c) a star like the Sun; the Oort cloud.
9. The red glow of an emission nebula (a) is emitted by warm gas falling onto the stars at the center; (b) is produced by hydrogen gas heated to high temperatures by massive stars within the nebula; (c) is a reflection of light from stars near the nebula; (d) is the unresolved light of many faint red stars within the nebula.
10. VIS The Rho Ophiuchus cloud, shown in Figure 11.12(a) (Dark Dust Cloud), is dark because (a) there are no stars in this region; (b) the stars in this region are young and faint; (c) starlight from behind the cloud does not penetrate the cloud; (d) the region is too cold to sustain stellar fusion.
11. Of the following telescopes, the one best suited to observing dark dust clouds is (a) an X-ray telescope; (b) a large visible-light telescope; (c) an orbiting ultraviolet telescope; (d) a radio telescope.
12. A protostar that will eventually turn into a star like the Sun is significantly (a) smaller; (b) more luminous; (c) fainter; (d) less massive than the Sun.
13. VIS The main difference between the Pleiades cluster (Figure 11.29a) and Omega Centauri (Figure 11.30a) is that the Pleiades cluster is much (a) larger; (b) younger; (c) farther away; (d) denser.
14. VIS In Figure 11.2 (Reddening), the effect of interstellar absorption on spectral lines is (a) to shift them to longer wavelengths; (b) to shift them to shorter wavelengths; (c) to leave their wavelengths unchanged; (d) to erase them.
15. VIS In Figure 11.23 (Newborn Star on the H–R Diagram), as the star moves from stage 6 to stage 7 it becomes (a) cooler and fainter; (b) hotter and smaller; (c) redder and brighter; (d) larger and cooler.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ The average density of interstellar gas within the Local Bubble is much lower than the value mentioned in the text—in fact, it is roughly 10^3 hydrogen atoms/m^3. Given that the mass of a hydrogen atom is 1.7×10^{-7} kg, calculate the total mass of interstellar matter contained within a bubble volume equal in size to planet Earth.
2. ■■ Calculate the frequency of 21-cm radiation. If interstellar clouds along our line of sight have radial velocities in the range 75 km/s (receding) to 50 km/s (approaching), calculate the range of frequencies and wavelengths over which the 21-cm line will be observed. ∞ *(Sec. 2.7)*
3. ■ Calculate the radius of a spherical molecular cloud whose total mass equals the mass of the Sun. Assume a cloud density of 10^{12} hydrogen molecules per cubic meter.
4. ■■ A beam of light shining through a dense molecular cloud is diminished in intensity by a factor of 2 for every 5 pc it travels. By how many magnitudes is the light from a background star dimmed if the total thickness of the cloud is 60 pc?
5. ■■ Estimate the escape speeds near the edges of the four emission nebulae listed in Table 11.1, and compare them with the average speeds of hydrogen nuclei in those nebulae. ∞ *(More Precisely 5-1)* Is it likely that the nebulae are held together by their own gravity?
6. ■■ For an interstellar gas cloud to contract, the average speed of its constituent particles must be less than half the cloud's escape speed. Will a (spherical) molecular hydrogen cloud of mass of 1000 solar masses, a radius 10 pc, and temperature of 10 K begin to collapse? Why or why not? ∞ *(More Precisely 5-1)*
7. ■ A protostar evolves from a temperature T = 3500 K and a luminosity L = 5000 times that of the Sun to T = 5000 K and L = 3 solar units. What is its radius (a) at the start, and (b) at the end of the evolution? ∞ *(Sec. 10.4)*
8. ■ Through roughly how many magnitudes does a three-solar-mass protostar decrease in brightness between stage 4 and stage 6?
9. ■■ What is the luminosity, in solar units, of a brown dwarf whose radius is 0.1 solar radii and whose surface temperature is 600 K (0.1 times that of the Sun)? ∞ *(Sec. 10.4)*
10. ■■ Approximating the gravitational field of our Galaxy as a mass of 10^{11} solar masses at a distance of 8000 pc (see Chapter 14), estimate the "tidal radius" of a 20,000-solar-mass star cluster—that is, the distance from the cluster center outside of which the tidal force due to the Galaxy overwhelms the cluster's gravity. ∞ *(Sec. 5.2)*

ACTIVITIES

Collaborative

1. The Messier catalog is a list of nebulae and other "fuzzy" objects in the night sky, compiled by 18th century astronomer Charles Messier to avoid confusion with his main interest, comets. Today, the catalog is a treasure trove of fascinating deep-sky objects. Many Messier objects are star-forming regions or star clusters. Star-forming regions mentioned in this chapter include M8 (the Lagoon Nebula), M16 (Eagle Nebula), M17 (Omega Nebula), M20 (Trifid Nebula), M42 (Orion Nebula). Interesting star clusters and associations include M6, M7, M11, M35, M37, M44, M45, M52, M67, and M103. Not all of these objects are easily observable on any given night, so consult a sky chart or do some research online, and make a list of which are visible. A small telescope will give the best results in most cases, and you may want to observe in shifts over the course of the night. For each Messier object on your list, find out what sort of object it is (emission nebula, association, young or old open cluster), carefully follow the finding instructions to locate it, and sketch it (or photograph it, if you have the equipment). Compare your sketch or photograph to images found in this book or online.

Individual

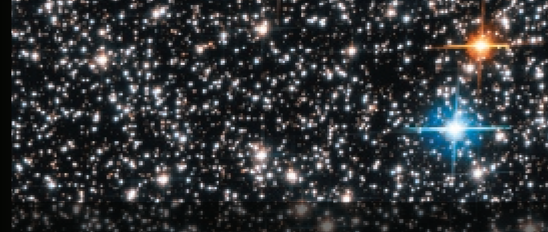
2. Observe the Milky Way on a dark, clear night away from city lights. Is it a continuous band of light across the sky or is it mottled? The parts of the Milky Way that appear missing are actually dark dust clouds lying relatively near the Sun. Identify the constellations in which you see these clouds. Make a sketch and compare with a star atlas. Find other small clouds in the atlas and try to find them with your eye or with binoculars.
3. The constellation Orion the Hunter is prominent in the winter sky. Its most noticeable feature is a short, straight row of three medium-bright stars: the famous belt of Orion. A line of stars extends from the easternmost star of the belt, toward the south. This is Orion's sword. Toward the bottom of the sword is the sky's most famous emission nebula, the Orion Nebula (M42). Observe the Orion Nebula with your eye, with binoculars, and with a telescope. What is its color? How can you account for this? With the telescope, try to find the Trapezium, a grouping of four stars in the center of the nebula. These are hot, young stars; their energy causes the Orion Nebula to glow.
4. The Trifid Nebula (M20) is another place where new stars are forming. It has been called a "dark night revelation, even in modest apertures." An 8- to 10-inch telescope is needed to see the nebula's triple-lobed structure. Ordinary binoculars reveal the Trifid as a hazy patch located in the constellation Sagittarius, set against the richest part of the Milky Way. What are the dark lanes? Why are other parts of the nebula bright? There have been reports of large-scale changes occurring in this nebula over the last 150 years, based on old drawings showing the nebula looking slightly different from its appearance today. Do you think it possible for an interstellar cloud to undergo a change in appearance on a time scale of years, decades, or centuries?

12

Stellar Evolution

The Lives and Deaths of Stars

Once nuclear fusion begins, a newborn star changes little in outward appearance for more than 90 percent of its lifetime. However, at the end of this period, as the star begins to run out of fuel and die, its properties once again change greatly. Aging stars travel along evolutionary tracks that take them far from the main sequence. The fate of a star depends primarily on its mass. Low-mass stars are destined to end their lives quiescently, their outer layers eventually escaping into interstellar space, while very massive stars die violently, in spectacular explosions of almost unimaginable fury. In either case, the deaths of stars enrich the Galaxy with newly created heavy elements. By continually comparing theoretical calculations with detailed observations of stars of all types, astronomers have refined the theory of stellar evolution into a precise and powerful tool for understanding the universe.



LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Explain why stars evolve off the main sequence.
- **LO2** Summarize the evolutionary stages a Sun-like star follows after it leaves the main sequence, and describe the resulting remnant.
- **LO3** Explain how white dwarfs in binary systems can become explosively active.
- **LO4** Summarize the sequence of events leading to the violent death of a massive star.
- **LO5** Describe the two types of supernova, and explain how each is produced.
- **LO6** Describe how observations of star clusters support the theory of stellar evolution.
- **LO7** Explain the origin of elements heavier than helium, and identify the significance of these elements for the study of stellar evolution.

THE BIG PICTURE

Understanding the story of the birth, development, and death of stars is one of the greatest accomplishments of 20th-century science. Yet no one has ever seen even a single star pass through all of its many varied evolutionary stages. Like archaeologists who examine bones and artifacts from long ago to learn more about the evolution of human culture, astronomers observe stars of many different ages to construct a consistent model of how stars evolve over billions of years.

◀ Resembling a cosmic hourglass or a celestial butterfly, this striking image captures hot gas released by a dying star about 3800 light-years away. Known as NGC 6302, or more informally as the Bug Nebula, this complex object is a planetary nebula—an old star shedding its outer layers over light-year dimensions as it ends its life. Its peculiar shape results from a belt of dust (dark lane at center) that obscures the dying star and partially blocks the rolling cauldrons of outwardly expelled gas. *(STScI)*

12.1 Leaving the Main Sequence

Most stars spend most of their lives on the main sequence of the H–R diagram. A star like the Sun, for example, after spending a few tens of millions of years in formation (stages 1–6 in Chapter 11), will reside on or near the main sequence (stage 7), with roughly constant temperature and luminosity, for some 10 billion years before evolving into something else. ∞ *(Sec. 11.4)* That "something else" is the topic of this chapter.

Stars and the Scientific Method

No one has ever witnessed the complete evolution of any star from birth to death. Stars take a very long time—millions, billions, even trillions of years—to evolve. ∞ *(Sec. 10.7)* Yet in less than a century, astronomers have developed a comprehensive theory of stellar evolution that is one of the best-tested in all of astronomy. How can we can talk so confidently about what took place billions of years in the past, and what will happen billions of years in the future? The answer is that we can observe billions of stars in the universe, enough to see examples of every stage of stellar development, allowing us to test and refine our theoretical ideas. Just as we can piece together a picture of the human life cycle by studying a snapshot of all the residents of a large city, so we can construct a picture of stellar evolution by studying the myriad stars we see in the night sky.

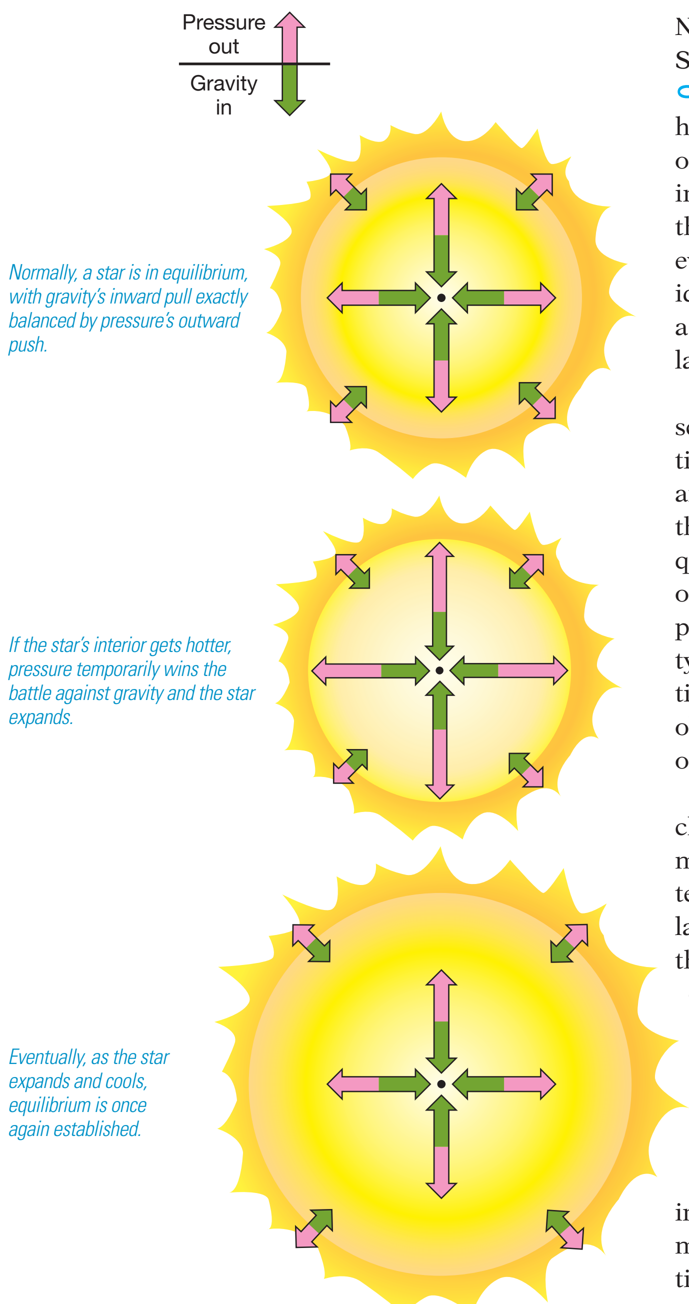
The modern theory of the lives and deaths of stars is another example of the scientific method in action. ∞ *(Sec. 0.5)* Faced with a huge volume of observational data, with little theory to organize or explain it, astronomers in the late 19th and early 20th centuries painstakingly classified and categorized the properties of the stars they observed. ∞ *(Sec. 10.5)* During the first half of the 20th century, as quantum mechanics yielded detailed insight into the behavior of light and matter on subatomic scales, theoretical understanding of key stellar properties fell into place. ∞ *(Sec. 2.6)* Since the 1950s, a truly comprehensive theory has emerged, tying together the basic disciplines of atomic and nuclear physics, electromagnetism, thermodynamics, and gravitation into a coherent whole. Today, theory and observation proceed hand in hand, each refining and validating the details of the other as astronomers continue to hone their understanding of stellar evolution.

Note that astronomers always use the term *evolution* in this context to mean change "during the lifetime of an individual star." Contrast this usage with the meaning of the term in biology, where evolution refers to changes in the characteristics of a *population* of plants or animals over many generations. In fact, populations of stars also evolve in the "biological" sense, as the overall composition of the interstellar medium (and hence of each new stellar generation) changes slowly over time due to nuclear fusion in stars. However, in astronomical parlance, *stellar evolution* refers to changes that occur during a single stellar lifetime.

Structural Change

On the main sequence, a star slowly fuses hydrogen into helium in its core. This process is usually called **core hydrogen burning,** but realize that here is another instance where astronomers use a familiar term in an unfamiliar way: To astronomers, "burning" always means nuclear fusion in a star's core, not a chemical reaction, such as the combustion of wood or gasoline in air, that we would normally mean in everyday speech. Chemical burning does not directly affect atomic nuclei.

As illustrated schematically in Figure 12.1, a main-sequence star is in a state of hydrostatic equilibrium, in which pressure's outward push exactly counteracts gravity's inward pull. ∞ *(Sec. 9.2)* This is a stable balance between



▲ **FIGURE 12.1 Hydrostatic Equilibrium** In a steadily burning star on the main sequence, the outward pressure exerted by hot gas balances the inward pull of gravity.

gravity and pressure, in which a small change in one always results in a small compensating change in the other. For example, as shown in the figure, a small increase in the star's central temperature leads to an increase in pressure, causing the star to expand and cool, thus recovering its equilibrium. Conversely, a small temperature decrease leads to a slight pressure decrease, and gravity causes the star to contract and heat up; again, equilibrium is restored. You should keep Figure 12.1 in mind as you study the various stages of stellar evolution described next. Much of a star's complex behavior can be understood in these simple terms.

As the hydrogen in the star's core is consumed, the balance between these opposing forces starts to shift. Both the star's internal structure and its outward appearance begin to change. The star leaves the main sequence. The subsequent stages of stellar evolution—the end of the star's life—depend critically on the star's mass. As a rule of thumb, we can say that low-mass stars die gently, while high-mass stars die catastrophically. The dividing line between these two very different outcomes lies around eight times the mass of the Sun, and in this chapter we will refer to stars of more than 8 solar masses as "high-mass" stars. However, within both the "high-mass" and the "low-mass" (i.e., less than 8 solar masses) categories, there are substantial variations, some of which we will point out as we proceed.

Rather than dwelling on the many details, we will concentrate on a few representative evolutionary sequences. We begin by considering the evolution of a fairly low-mass star like the Sun. Later, we will broaden our discussion to include all stars, large and small.

CONCEPT CHECK

In what sense is the Sun stable?

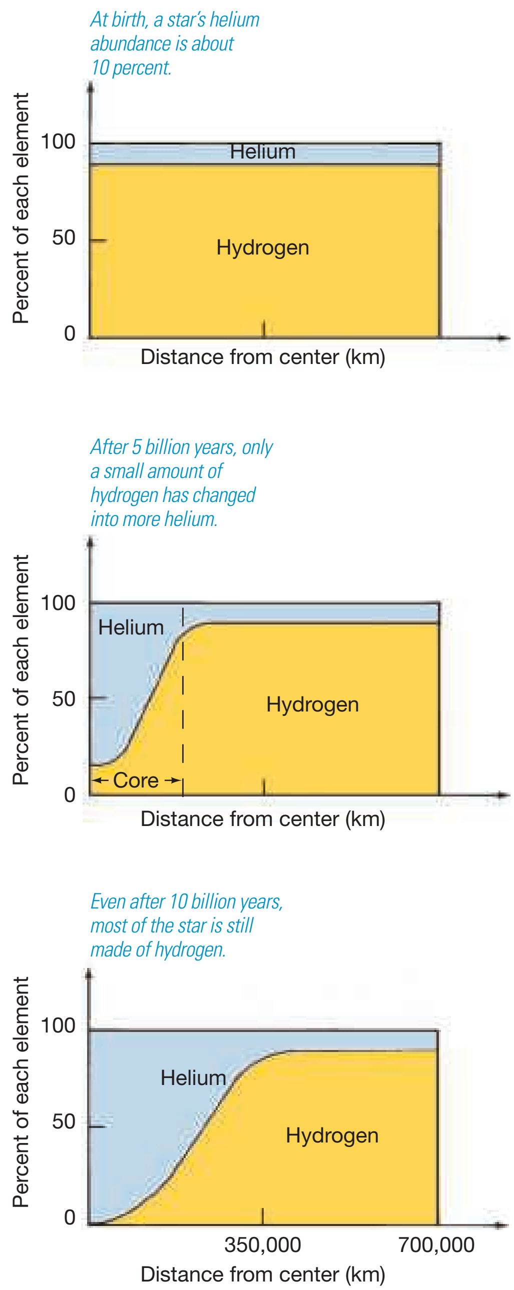
12.2 Evolution of a Sun-like Star

Figure 12.2 illustrates how the interior composition of a main-sequence star changes as the star ages. The star's helium content increases fastest at the center, where temperatures are highest and the burning (creating helium from hydrogen) is fastest. ∞ *(Sec. 9.5)* The helium content also increases near the edge of the core, but more slowly because the burning rate is less rapid there. The inner, helium-rich region becomes larger and more hydrogen deficient as the star continues to shine.

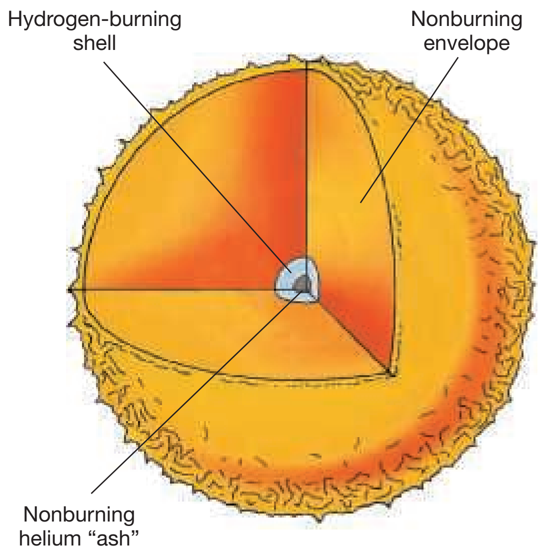
Stages 8 and 9—Subgiant to Red Giant

Recall from Chapter 9 that a temperature of 10^7 K is needed to fuse hydrogen into helium. Only above that temperature do colliding hydrogen nuclei (that is, protons) have enough speed to overwhelm their mutual electromagnetic repulsion. ∞ *(Sec. 9.5)* Because helium nuclei (with two protons each, compared to one for hydrogen) carry a greater positive charge, their electromagnetic repulsion is greater, and so higher temperatures are needed to cause them to fuse. The core temperature at this stage is too low for helium fusion to begin. Eventually, hydrogen becomes depleted at the center, the nuclear fires there subside, and the location of principal burning moves to higher layers in the core. An inner core of nonburning pure helium starts to grow.

Without nuclear burning to maintain it, the outward-pushing gas pressure weakens in the helium inner core; however, the inward pull of gravity does not. Once the pressure is relaxed—even a little—structural changes in the star become inevitable. As soon as hydrogen becomes substantially depleted, about 10 billion years after the star arrived on the main sequence, the helium core begins to contract.



▲ **FIGURE 12.2 Solar Composition Change** Theoretical estimates of the changes in a Sun-like star's composition show how hydrogen (yellow) and helium (blue) abundance vary within the star from birth to death (top to bottom).



▲ FIGURE 12.3 **Hydrogen Shell Burning** As a star's core converts more and more of its hydrogen into helium, the hydrogen in the shell surrounding the nonburning helium "ash" burns ever more violently. By the time the star has reached the bottom of the giant branch, its core has shrunk to a few tens of thousands of kilometers in diameter, and its surface is 10 times the star's original size.

The shrinking helium core releases gravitational energy, driving up the central temperature, heating the overlying layers of the core, and causing the hydrogen there to fuse even more rapidly than before. Figure 12.3 depicts this **hydrogen shell-burning** stage, in which hydrogen burns at a furious rate in a relatively thin layer surrounding the nonburning inner core of helium "ash." The hydrogen shell generates energy faster than did the original main-sequence star's hydrogen-burning core, and the shell's energy production continues to increase as the helium core contracts. Strange as it may seem, the star's response to the disappearance of the nuclear fire at its center is to get brighter!

The pressure exerted by this enhanced hydrogen burning causes the star's nonburning outer layers to increase in radius. Not even gravity can stop them. Even as the core shrinks and heats up, the overlying layers expand and cool. The star, aged and unbalanced, is on its way to becoming a red giant. The change from main-sequence star to red giant takes about 100 million years.

We can trace these large-scale changes on an H–R diagram. Figure 12.4 shows the star's path away from the main sequence, labeled as stage 7. ∞ *(Sec. 11.3)* The star evolves to the right on the diagram, its surface temperature dropping while its luminosity increases only slightly. The star's roughly horizontal track from the main sequence (stage 7) to stage 8 on the figure is called the **subgiant branch.** By stage 8, the star's radius has increased to about three times the radius of the Sun. The nearly vertical (constant temperature) path followed by the star between stages 8 and 9 is known as the **red giant branch** of the H–R diagram. (Figure 12.3 corresponds to a point just after stage 8, as the star begins to ascend the giant branch.)

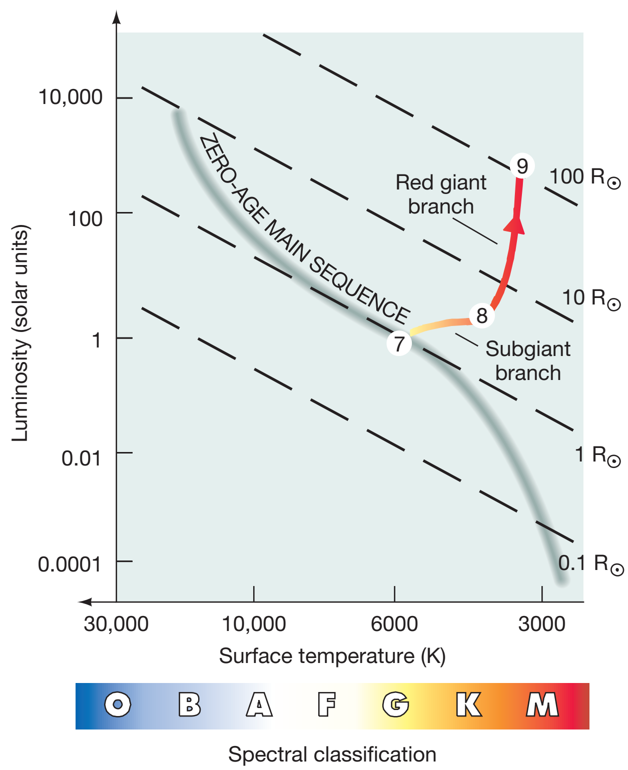
The red giant is huge. By stage 9 its luminosity is many hundreds of times the solar value. Its radius is around 100 solar radii—about the size of Mercury's orbit. In contrast, its helium core is surprisingly small, less than 1/1000 the size of the entire star, or just a few times larger than Earth. Continued shrinkage of the red giant's core has compacted its helium gas to a density of approximately 10^8 kg/m^3—10,000 times denser than any material found on Earth. About 25 percent of the mass of the entire star is packed into its planet-sized core.

A familiar example of a low-mass star in the red giant phase is the KIII giant Arcturus ∞ *(Figure 10.14)*, one of the brightest stars in our night sky. Its mass is about 1.5 times that of the Sun. Currently in the hydrogen shell-burning stage and ascending the red giant branch, its radius is some 21 times the solar value. ∞ *(Table 10.4)* It emits more than 160 times more energy than the Sun, much of it in the infrared part of the spectrum.

Stage 10—Helium Fusion

This simultaneous contraction of the red giant's core and expansion of its envelope—the nonburning layers surrounding the core—does not continue indefinitely. A few hundred million years after a solar-mass star leaves the main sequence, the central temperature reaches the 10^8 K needed for helium to fuse into carbon, and the nuclear fires reignite.

For stars comparable in mass to the Sun, the high densities and pressures found in the stage-9 core mean that the onset of helium fusion is a very violent event. Once the burning starts, the core cannot respond quickly enough to the rapidly changing conditions within it, and its temperature rises sharply in a

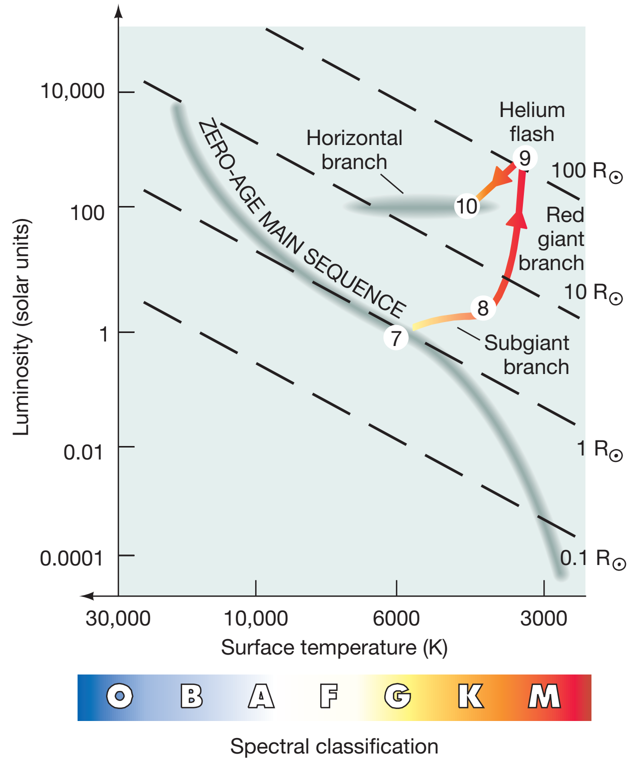


◀ FIGURE 12.4 **Red Giant on the H–R Diagram** As its helium core shrinks and its outer envelope expands, the star leaves the main sequence (stage 7). At stage 8, the star is well on its way to becoming a red giant. The star continues to brighten and grow as it ascends the red giant branch to stage 9.

runaway explosion called the **helium flash.** For a few hours, the helium burns ferociously, like an uncontrolled bomb. Eventually, the star's structure "catches up" with the flood of energy dumped into it by helium burning. The core expands, its density drops, and equilibrium is restored as the inward pull of gravity and the outward push of gas pressure come back into balance. The core, now stable, begins to burn helium into carbon at temperatures well above 10^8 K.

The helium flash terminates the star's ascent of the red giant branch of the H–R diagram. Yet despite the explosive detonation of helium in the core, the flash does *not* increase the star's luminosity. Rather, the helium flash produces an expansion and cooling of the core that ultimately results in a *reduction* in the energy output as the star jumps from stage 9 to stage 10. As indicated in Figure 12.5, the surface temperature is now higher than it was on the red giant branch, although the luminosity is less than at the helium flash. This adjustment in the star's properties occurs quite quickly—in about 100,000 years.

At stage 10 our star is now stably burning helium in its inner core and fusing hydrogen in a shell surrounding that core. It resides in a well-defined region of the H–R diagram known as the **horizontal branch,** where core helium-burning stars remain for a time before resuming their journey around the H–R diagram. The star's specific position within this region is determined mostly by its mass—not its original mass, but whatever mass remains after the red giant phase. The two masses differ because strong stellar winds can eject large amounts of matter—as much as 20–30 percent of the initial mass—from a red giant's surface. The more massive stars have thicker envelopes and lower surface temperatures at this stage, but all stars have roughly the same luminosity after the helium flash. As a result, stage-10 stars tend to lie along a horizontal line on the H–R diagram, with more massive stars to the right and less massive ones to the left.



▲ **FIGURE 12.5 Horizontal Branch** A large increase in luminosity occurs as a star ascends the red giant branch, ending in the helium flash. The star then settles down into another equilibrium state at stage 10, on the horizontal branch.

Stage 11—A Red Giant Again

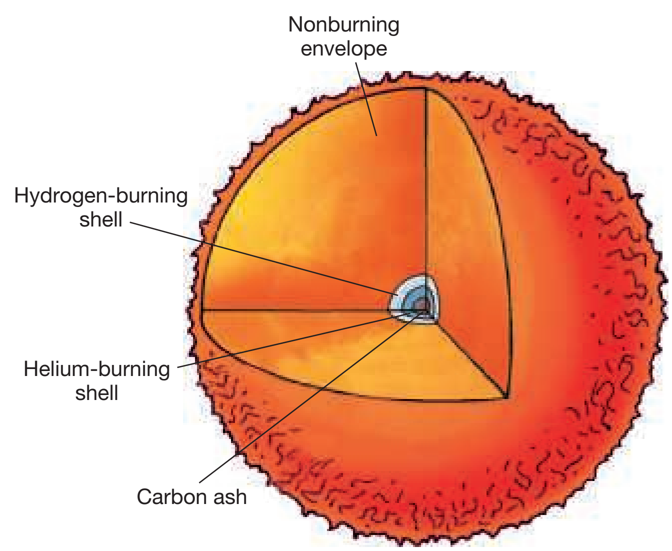
Nuclear reactions in stars proceed at rates that increase very rapidly with temperature. At the extremely high temperatures found in the core of a horizontal-branch star, the helium fuel doesn't last long—no more than a few tens of millions of years after the initial flash.

As helium fuses to carbon, a new carbon-rich inner core begins to form and phenomena similar to the earlier buildup of helium occur. Helium becomes depleted at the center, and eventually fusion ceases there. The nonburning carbon core shrinks in size—even as its mass increases due to helium fusion—and heats up as gravity pulls it inward, causing the hydrogen- and helium-burning rates in the overlying layers to increase. The star now contains a contracting carbon-ash inner core surrounded by a helium-burning shell, which is in turn surrounded by a hydrogen-burning shell (Figure 12.6). The outer envelope of the star expands, much as it did earlier in the first red giant stage. By the time it reaches stage 11 in Figure 12.7, the star has become a swollen red giant for a second time.

The burning rates in the shells surrounding the inner core are much fiercer during the star's second trip into the red giant region, and the radius and luminosity increase to values even greater than those reached during the first visit (stage 9). Its carbon core continues to shrink, driving the hydrogen- and helium-burning shells to higher and higher temperatures and luminosities. To distinguish this second visit to the red giant region from the first, the star's evolutionary track during this stage is often referred to as the *asymptotic giant branch.*[1]

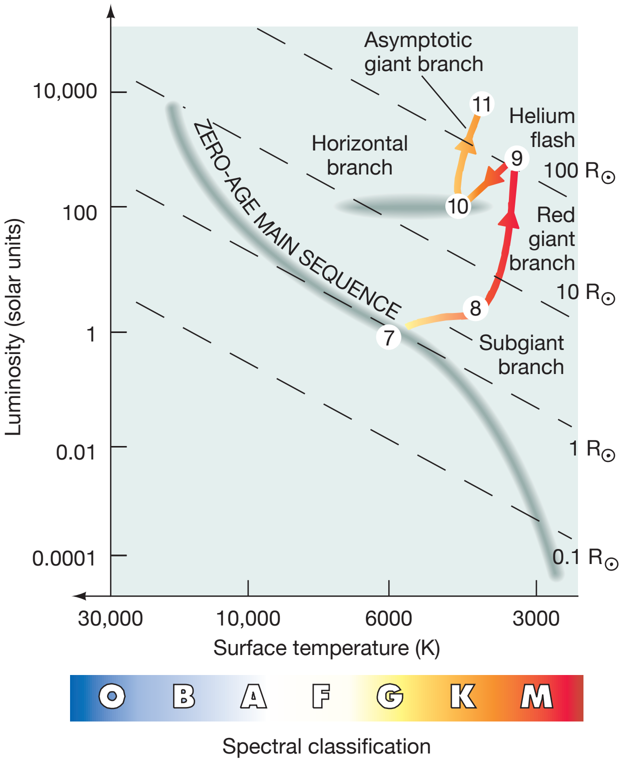
CONCEPT CHECK

Why does a star get brighter as it runs out of fuel in its core?



▲ **FIGURE 12.6 Helium Shell Burning** Within a few million years after the onset of helium burning (stage 9), carbon ash accumulates in the star's inner core (not to scale). Above this core, hydrogen and helium are still burning in concentric shells.

[1]The term is borrowed from mathematics. An asymptote to a curve is a second curve that approaches ever closer to the first as the two are extended to infinity. Theoretically, if the star remained intact, the asymptotic-giant branch would approach the red giant branch from the left as the luminosity increased and would effectively merge with the red giant branch near the top of Figure 12.10. However, a Sun-like star will not live long enough for that to occur.



▲ **FIGURE 12.7 Reascending the Giant Branch** A carbon-core star reenters the giant region of the H–R diagram (stage 11) for the same reason it evolved there the first time around: Lack of nuclear fusion at the center causes the core to contract and the overlying layers to expand.

Table 12.1 summarizes the key stages through which our solar-mass star evolves. It is a continuation of Table 11.2, except that the density units are now the more convenient kilograms per cubic meter and we now express radii in units of the solar radius. As in Chapter 11, The numbers in the "Stage" column refer to the evolutionary stages noted in the figures and discussed in the text. Figure 12.8 illustrates the stages through which a G-type star like our Sun will evolve over the course of its lifetime.

12.3 The Death of a Low-Mass Star

As our star moves from stage 10 to stage 11, its envelope swells while its inner carbon core, too cool for further nuclear burning, continues to contract. If the central temperature could become high enough for carbon fusion to occur, still heavier elements could be synthesized, and the newly generated energy might again support the star, restoring for a time the equilibrium between gravity and pressure. For solar-mass stars, however, this does not occur—a lot more mass is needed, as we will see in the next section. The temperature never reaches the 600 million kelvins needed for new nuclear reactions to occur. The red giant is now very close to the end of its nuclear-burning lifetime.

Stage 12—A Planetary Nebula

Our aging star is now in quite a predicament. Its carbon core is, for all practical purposes, dead, while the outer hydrogen- and helium-burning shells consume fuel at a furious and increasing rate. As it expands, cools, and reascends the giant branch, the star begins to fall apart. Driven by the intense radiation from within, its outer layers begin to drift away into interstellar space. Slowly at first, then more rapidly as the core luminosity increases, the star loses virtually its entire envelope in less than a million years. The former red giant now consists of two distinct pieces: the exposed core, very hot and still very luminous, surrounded by a cloud of dust and cool gas—the escaping envelope—expanding away at a typical speed of a few tens of kilometers per second.

As the core exhausts its last remaining fuel, it contracts and heats up, moving to the left in the H–R diagram. Eventually, it becomes so hot that its ultraviolet radiation ionizes the inner parts of the surrounding cloud, producing a spectacular display called a **planetary nebula** (see Figure 12.9). The terminology is misleading, for these objects have nothing to do with planets. It originated in the

ANIMATION/VIDEO
Death of the Sun Part I

ANIMATION/VIDEO
Death of the Sun Part II

▼ **FIGURE 12.8 G-type Star Evolution** INTERACTIVE Artist's conception of the relative sizes and changing colors of a normal G-type star (such as our Sun) during its formative stages, on the main sequence, and while passing through the red giant and white dwarf stages. At maximum swelling, the red giant is approximately 70 times the size of its main-sequence parent; the core of the giant is about $^{1}/_{15}$ the main-sequence size and would be barely discernible if this figure were drawn to scale. The duration of time spent in the various stages—protostar, main-sequence star, red giant, and white dwarf—is roughly proportional to the lengths shown in this imaginary trek through space.

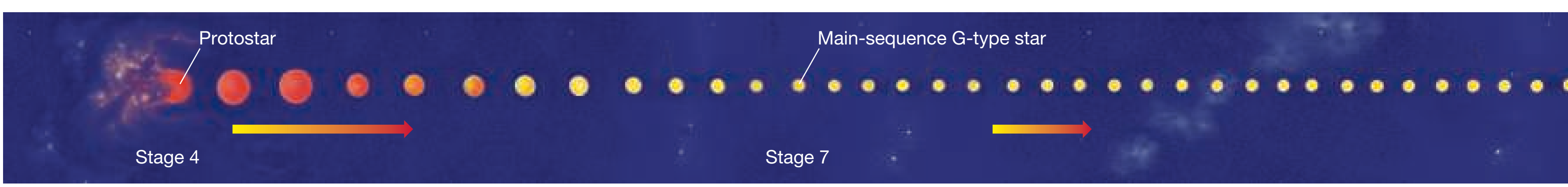


TABLE 12.1 Evolution of a Sun-like Star

Stage	Approx. Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	1.5×10^7	6,000	10^5	7×10^5	1	Main-sequence star
8	10^8	5×10^7	4,000	10^7	2×10^6	3	Subgiant
9	10^5	10^8	4,000	108	7×10^7	100	Red giant/helium flash
10	5×10^7	2×10^8	5,000	10^7	7×10^6	10	Horizontal branch
11	10^4	2.5×10^8	4,000	10^8	4×10^8	500	Red giant (AGB)
	10^5	3×10^8	100,000	10^{10}	10^4	0.01	Carbon core
12	—	—	3,000	10^{-17}	7×10^8	1,000	Planetary nebula*
13	—	10^8	50,000	10^{10}	10^4	0.01	White dwarf
14	—	Close to 0	Close to 0	10^{10}	10^4	0.01	Black dwarf

*Values in columns 2–7 refer to the envelope.

18th century when, viewed at poor resolution through small telescopes, these shells of gas looked to some astronomers like the circular disks of planets in our solar system.

The mechanism by which planetary nebulae shine is very similar to that powering the emission nebulae we studied earlier—ionizing radiation from a hot star embedded in a cool gas cloud. *(Sec. 11.2)* However, these two classes of object have very different origins and represent completely separate phases of stellar evolution. The emission nebulae in Chapter 11 were the signposts of recent stellar birth. Planetary nebulae indicate impending stellar death.

Astronomers once thought that the escaping giant envelope would be more or less spherical in shape, completely surrounding the core in three dimensions, just as it had while still part of the star. Figure 12.9(a) shows an example in which this may well be the case. The nebula looks brighter near the edges because there is more emitting gas along the line of sight there, creating the illusion of a bright ring. However, such cases now seem to be in the minority. There is growing evidence that the final stages of red giant mass loss are often decidedly *non*spherical. The Ring Nebula shown in Figure 12.9(b) may very well *be* a ring and not just our view of a glowing shell of gas as was once thought. As illustrated in Figure 12.9(c) and (d), some planetary nebulae exhibit much more complex structures, suggesting that the star's environment—including the existence of a binary companion—can play an important role in determining the nebula's shape and appearance.

The central star fades and eventually cools, and the expanding gas cloud becomes more and more diffuse, gradually dispersing into interstellar space. In doing so it plays a vital role in the evolution of our Galaxy. During the final stages of the red giant's life, nuclear reactions between carbon and unburned helium in the core create oxygen, and in some cases even heavier elements, such as neon and magnesium. Some of these reactions also release neutrons

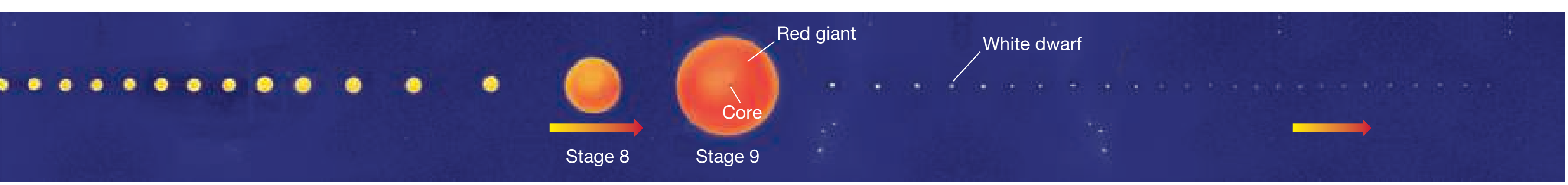
MA ANIMATION/VIDEO Helix Nebula

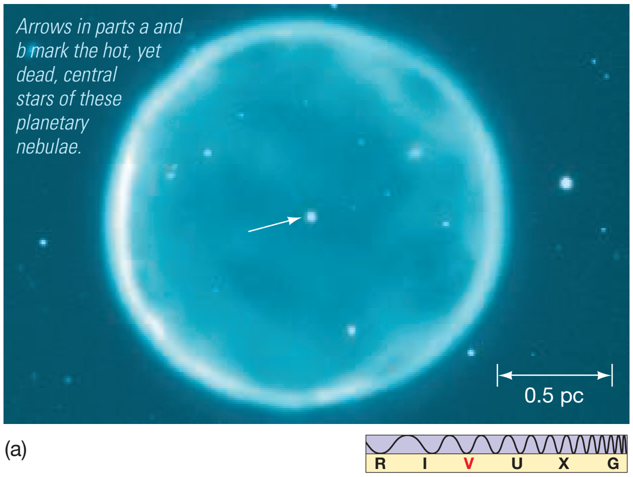
MA ANIMATION/VIDEO Helix Nebula Animation

MA ANIMATION/VIDEO Helix Nebula White Dwarf

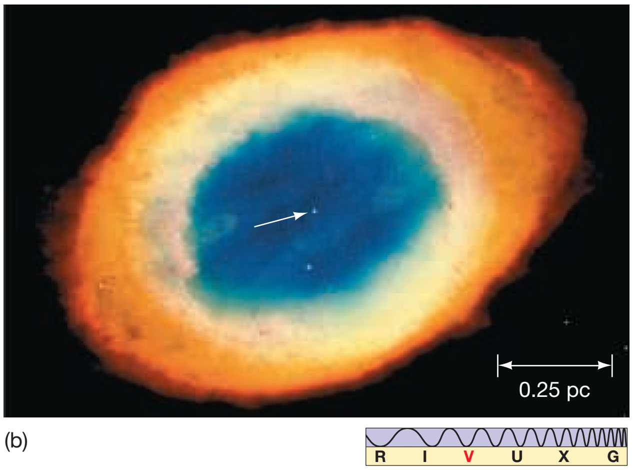
MA ANIMATION/VIDEO White Dwarf Cooling Sequence

MA ANIMATION/VIDEO Bi-Polar Planetary Nebula





(a)



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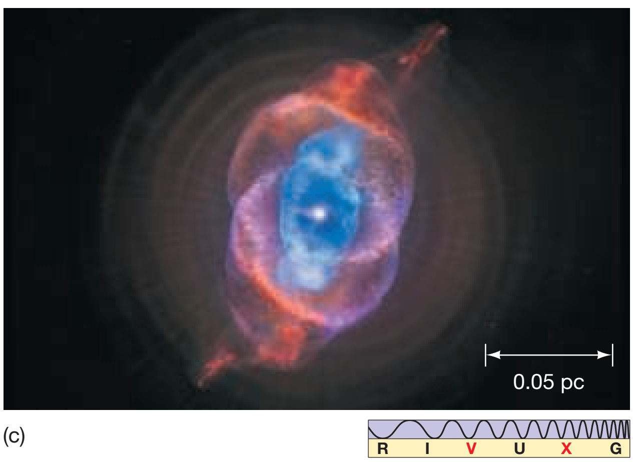

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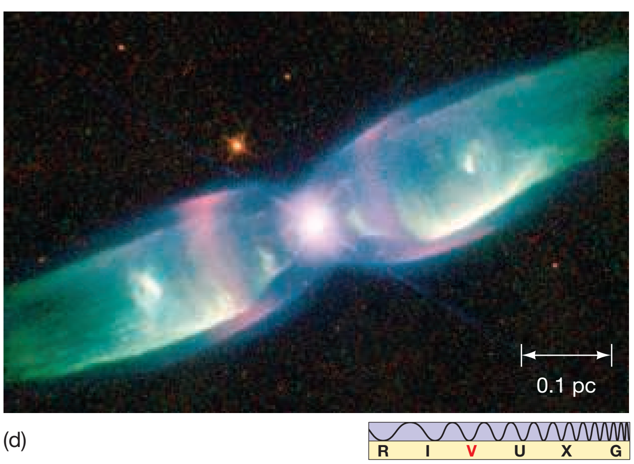


(d)

that, carrying no electrical charge, have no electrostatic repulsion to overcome and hence can interact with existing nuclei to form still heavier elements. ∞ *(Secs. 2.6, 9.5)* All of these elements—helium, carbon, oxygen, and heavier—are "dredged up" from the depths of the core into the envelope by convection during the star's final years and enrich the interstellar medium when the giant envelope escapes. ∞ *(Sec. 9.2)* The evolution of low-mass stars is the source of virtually all of the carbon-rich dust observed throughout the plane of our Galaxy. ∞ *(Sec. 11.1)*

Dense Matter

Before the shrinking carbon core can become hot enough for carbon to fuse, the rising pressure stops the contraction and stabilizes the temperature. However, this pressure is not the "normal" thermal pressure of high-speed particles in a very hot gas. ∞ *(More Precisely 5-1)* Instead, as we now discuss, the core enters a state in which the free electrons in the core—a vast sea of charged particles stripped from their parent nuclei by the ferocious heat in the stellar interior—play a critical role in determining the star's future.

The core density at this stage (stage 12 in Table 12.1) is enormous—about 10^{10} kg/m^3. This density is much higher than anything we have seen so far in our study of the cosmos. A single cubic centimeter of core matter would weigh 1000 kg on Earth—a ton of matter compressed into a volume about the size of a grape! Under these extreme conditions, a law of quantum physics known as the *Pauli exclusion principle* comes into play, preventing the electrons in the core from being crushed any closer together. (In fact, the core was in a similar high-density state at the moment of helium ignition, causing the helium flash.)

In essence, the electrons behave like tiny rigid spheres that can be squeezed relatively easily up to the point of contact, but become virtually incompressible thereafter. By stage 12 the pressure in the carbon core resisting the force of gravity is supplied almost entirely by tightly packed electrons, and this pressure brings the core back into equilibrium at a central temperature of about 300 million K—too cool to fuse carbon into heavier elements. This stage represents the maximum compression that the star can achieve—there is simply not enough matter in the overlying layers to bear down any harder. Supported by the resistance of its electrons to further compression, the contraction of the core stops.

Stage 13—A White Dwarf

Formerly concealed by the atmosphere of the red giant, the carbon core becomes visible as a *white dwarf* as the envelope recedes. ∞ *(Sec. 10.4)* The core is small, about the size of Earth, with a mass about half that of the Sun. Shining only by stored heat, not by nuclear reactions, this object has a white-hot surface when it first becomes visible, although it appears dim because of its small size. This is stage 13 of Table 12.1. The approximate path followed by the star on the H–R

◄ **FIGURE 12.9 Planetary Nebulae** The ejected envelopes of dying stars can take on a bewildering variety of forms. (a) Abell 39, some 2100 pc away, is a classic planetary nebula shedding a spherical shell of gas about 1.5 pc across; (b) the Ring Nebula, perhaps the most famous of all planetaries at 1500 pc distant and 0.5 pc across, is probably a genuine ring, yet too small and dim to be seen with the naked eye; (c) the Cat's Eye Nebula, about 1000 pc away and 0.1 pc across, is an example of a much more complex planetary nebula, possibly produced by a pair of binary stars (unresolved at center) that have both shed envelopes (red seen in visible light, blue in X-rays); (d) M2-9, some 600 pc away, shows surprising twin jets of glowing gas racing outward from the central star at speeds of about 300 km/s. *(AURA; NASA)*

▶ **FIGURE 12.10 White Dwarf on H–R Diagram** INTERACTIVE A star's passage from the horizontal branch (stage 10) to the white dwarf stage (stage 13) creates an evolutionary path that cuts across the H–R diagram.

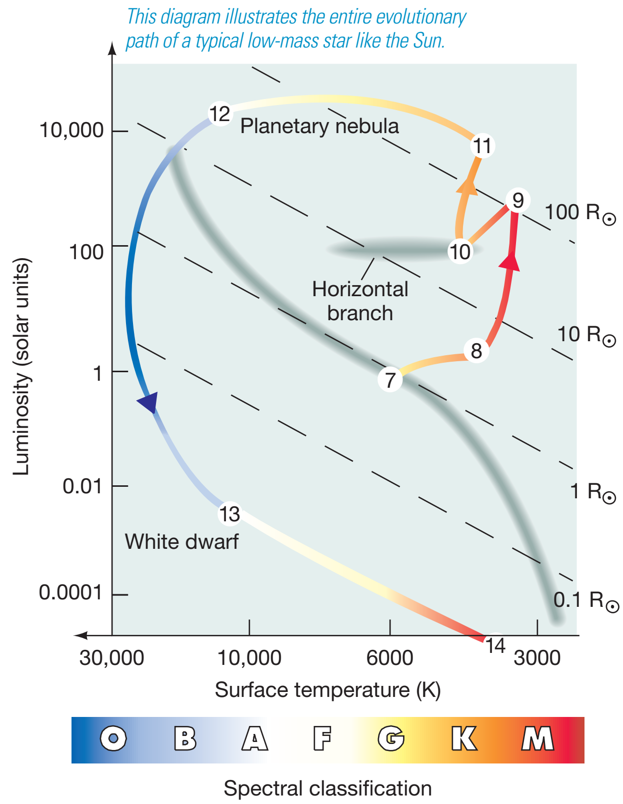


diagram as it evolves from a stage 11 red giant to a stage 13 white dwarf is shown in Figure 12.10.

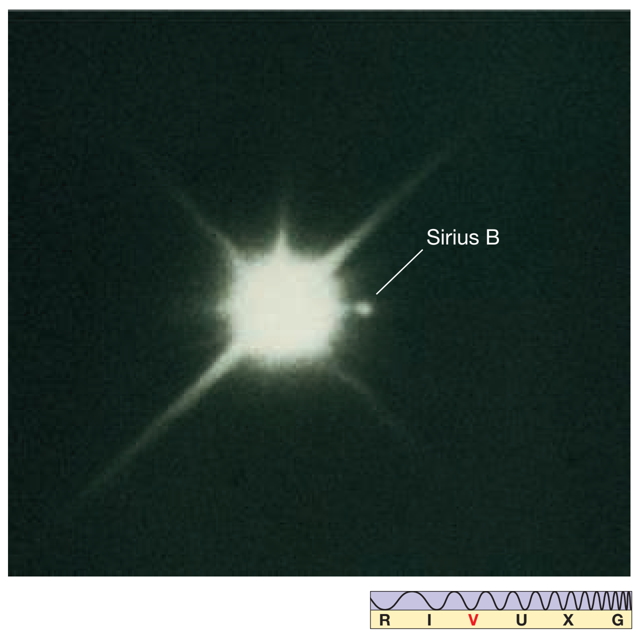
Not all white dwarfs are seen as the cores of planetary nebulae. Several hundred have been discovered "naked," their envelopes expelled to invisibility long ago. Figure 12.11 shows an example of a white dwarf, Sirius B, that happens to lie particularly close to Earth; it is the faint binary companion of the much brighter Sirius A. ∞ *(Sec. 10.7)* Some of its properties are listed in Table 12.2. With more than a solar mass of material packed into a volume smaller than Earth, Sirius B is about a million times denser than anything known in the solar system. Sirius B has an unusually high mass for a white dwarf. It is thought to be the descendent of a star roughly four times the mass of the Sun.

Hubble Space Telescope observations of nearby globular clusters have revealed the white dwarf sequences long predicted by theory but previously too faint to detect at such large distances. Figure 12.12(a) shows a ground-based view of the globular cluster M4, lying 2100 pc from Earth. Part (b) of the figure shows a *Hubble* close-up of a small portion of the cluster, revealing dozens of white dwarfs (some marked) among the cluster's much brighter main-sequence, red giant, and horizontal-branch stars. When plotted on an H–R diagram (see Figure 12.26), the white dwarfs fall nicely along the line indicated on Figure 12.10.

The white dwarf continues to cool and dim with time, following the white–yellow–red line near the bottom of Figure 12.10, eventually becoming a **black dwarf**—a cold, dense, burned-out cinder in space. This is stage 14 of Table 12.1, the graveyard of stars. The cooling dwarf does not shrink much as it fades away, however. Even though its heat is leaking away into space, gravity does not compress it further. Its tightly packed electrons will support the star even as its temperature drops (after trillions of years) almost to absolute zero. As the dwarf cools, it remains about the size of Earth.

Most white dwarfs are composed of carbon and oxygen, but theory predicts that very low-mass stars (less than about one-quarter the mass of the Sun) will never reach the point of helium fusion. Instead, their cores will become supported by the resistance of its electrons to further compression before the central temperature reaches the 100 million kelvins needed for helium to fuse. The interiors of such stars are completely convective, ensuring that fresh hydrogen continually mixes from the envelope into the core. As a result, unlike the case of the Sun illustrated in Figure 12.2, a nonburning helium inner core never appears, and eventually *all* of the star's hydrogen is converted to helium, forming a *helium white dwarf*.

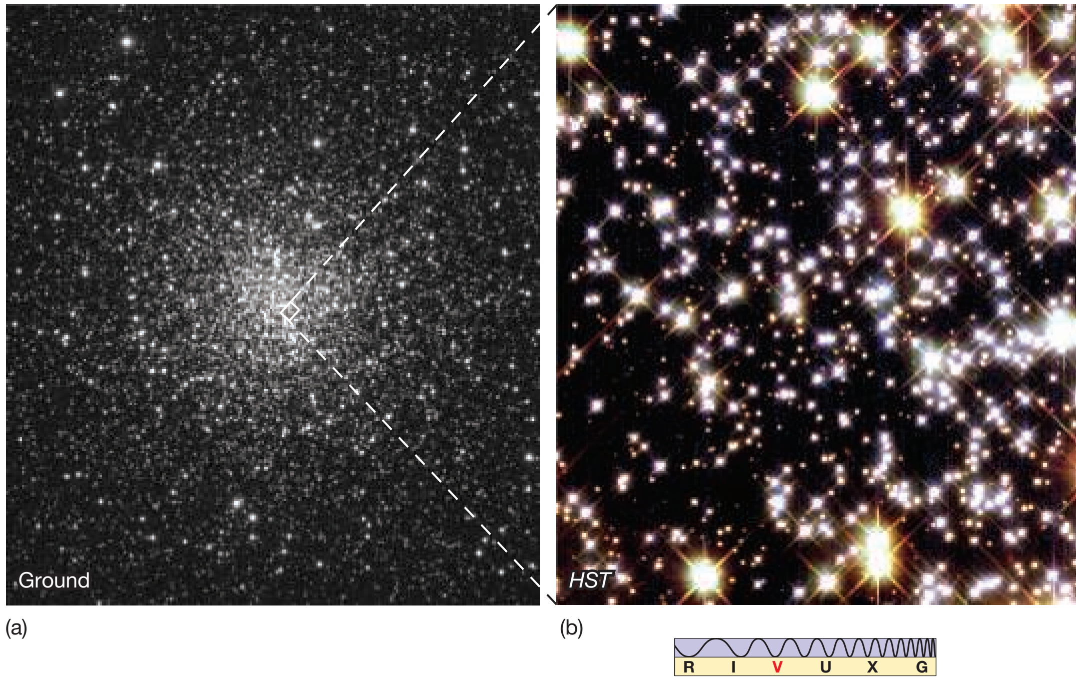
The time needed for this kind of transformation to occur is very long—hundreds of billions of years—so no helium white dwarfs have ever actually formed in this way. ∞ *(Sec. 10.7)* However, if a solar-mass star is a member of a *binary* star system, it is possible for its envelope to be stripped away during the red giant stage by the gravitational pull of its companion, exposing the helium core



▲ **FIGURE 12.11 Sirius Binary System** Sirius B (the speck of light to the right of the much larger and brighter Sirius A) is a white dwarf star, a companion to Sirius A. The "spikes" on the image of Sirius A are not real; they are caused by the support struts of the telescope. *(Palomar Observatory)*

TABLE 12.2 Sirius B—A Nearby White Dwarf

Mass	1.1 Solar masses
Radius	0.008 Solar radii (5500 km)
Luminosity (total)	0.04 Solar luminosities
Surface temperature	24,000 K
Average density	3×10^9 kg/m^3



▶ **FIGURE 12.12 Distant White Dwarfs** (a) The globular cluster M4, as seen through a large ground-based telescope at Kitt Peak National Observatory in Arizona, is the closest globular cluster to us, at 1700 pc away; it spans some 16 pc. (b) A peek at M4's "suburbs" by the *Hubble Space Telescope* shows nearly a hundred white dwarfs within a small 0.2 square-parsec region. *(AURA; NASA)*

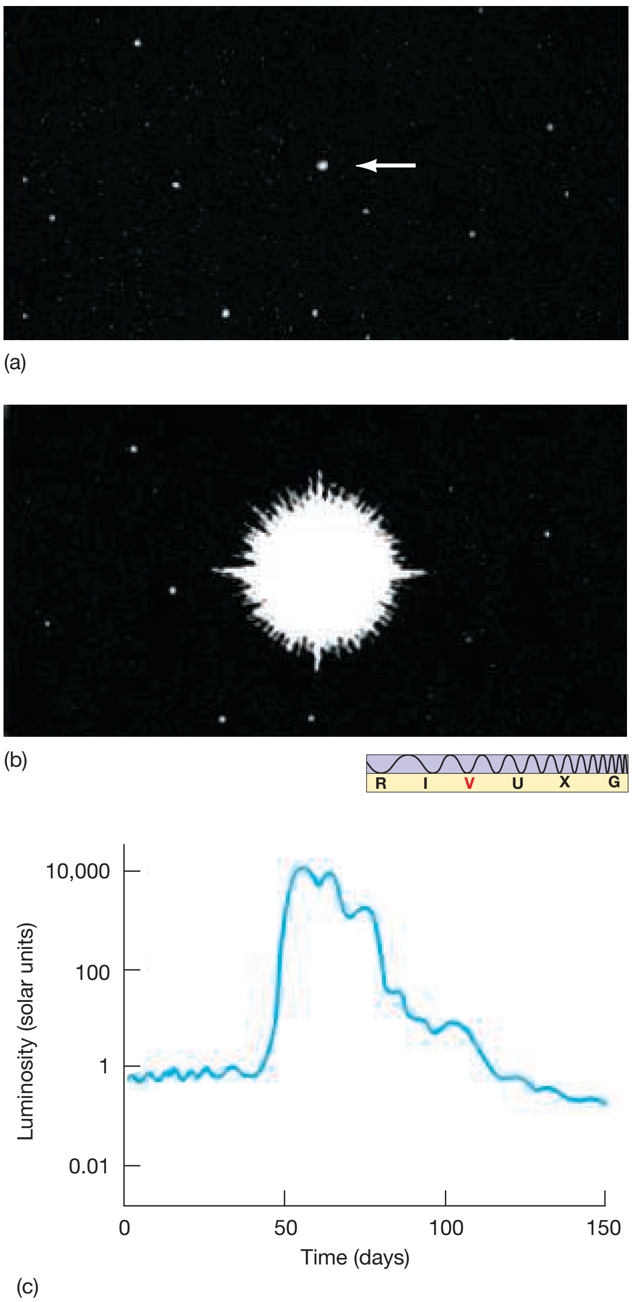
and terminating the star's evolution before helium fusion can begin. Several such low-mass helium white dwarfs have in fact been detected in binary systems in our Galaxy.

In stars much more massive than the Sun (close to the 8-solar mass limit on "low-mass" stars at the time the carbon core forms—see Section 12.4), temperatures in the core may become high enough that oxygen can combine with helium to form neon, eventually leading to the formation of a rare *neon–oxygen white dwarf* when fusion finally stops.

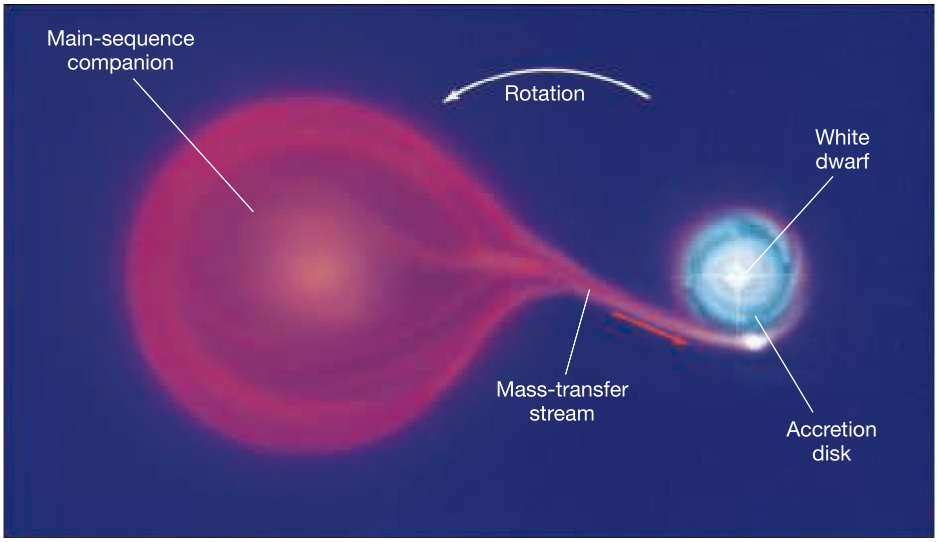
Novae

In some cases, the white dwarf stage does not represent the end of the road for a Sun-like star. Given the right circumstances, it is possible for a white dwarf to become explosively active, in the form of a highly luminous **nova** (plural: novae). The word *nova* means "new" in Latin, and to early observers, these stars did indeed seem new as they suddenly appeared in the night sky. Astronomers now recognize that a nova is what we see when a white dwarf undergoes a violent explosion on its surface, resulting in a rapid, temporary increase in luminosity. Figures 12.13(a) and (b) illustrate the brightening of a typical nova over a period of 3 days. Figure 12.13(c) shows the nova's light curve, demonstrating how the luminosity rises dramatically in a matter of days, then fades slowly back to normal over the course of several months. On average, two or three novae are observed each year.

What could cause such an explosion on a faint, dead star? The energy involved is far too great to be explained by flares or other surface activity, and as we have just seen, there is no nuclear activity in the dwarf's interior. The answer to this question lies in the white dwarf's surroundings. If the white dwarf is isolated,



◀ **FIGURE 12.13 Nova** Shown here is Nova Herculis 1934 in (a) March 1935 and (b) May 1935, after brightening by a factor of 60,000. (c) The light curve of a typical nova displays a rapid rise followed by a slow decline in the light received from the star, in good agreement with the explanation of the nova as a nuclear flash on a white dwarf's surface. *(UC/Lick Observatory)*



◄ **FIGURE 12.14 Close Binary System** If a white dwarf in a binary system is close enough to its companion, its gravitational field can tear matter from the companion's surface. Notice that the matter does not fall directly onto the white dwarf's surface. Instead, it forms an accretion disk of gas spiraling down onto the dwarf.

then it will indeed cool and ultimately become a black dwarf, as just described. However, should the white dwarf be part of a binary system in which the other star is either a main-sequence star or a giant, an important new possibility exists.

If the distance between the dwarf and the other star is small enough, the dwarf's gravitational field can pull matter—primarily hydrogen and helium—away from the surface of the companion. Because of the binary's rotation, material leaving the companion does not fall directly onto the white dwarf. Instead, it "misses" the dwarf, loops around behind it, and goes into orbit around it, forming a swirling, flattened disk of matter called an **accretion disk,** as shown in Figure 12.14. As it builds up on the white dwarf's surface, the stolen gas becomes hotter and denser. Eventually, its temperature exceeds 10^7 K and the hydrogen ignites, fusing into helium at a furious rate. This surface-burning stage is as brief as it is violent. The star suddenly flares up in luminosity, then fades away as some of the fuel is exhausted and the rest is blown off into space (Figure 12.15). If the event happens to be visible from Earth, we see a nova.

Once the nova explosion is over and the binary has returned to normal, the mass-transfer process can begin again. Astronomers know of many *recurrent novae*—stars that have been observed to "go nova" several times over the course of a few decades. Such systems can, in principle, repeat their violent outbursts many dozens, if not hundreds, of times.

DATA POINTS

Stellar Evolution

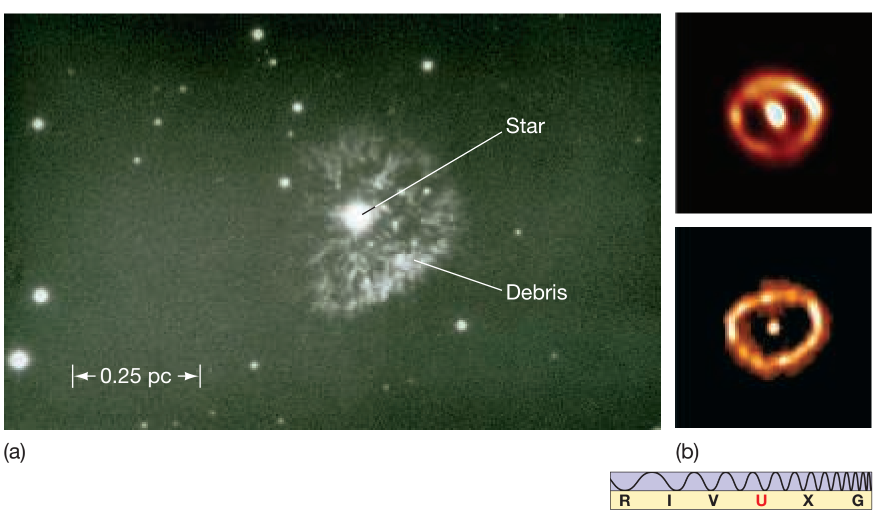
Forty percent of students had difficulty describing the basic evolutionary processes occurring once a star leaves the main sequence. Some key points:

- Stars begin their lives on the Main Sequence, the most massive at the top left, the least massive at the lower right.
- Stars do not evolve along the Main Sequence; they evolve away from it as they age.
- Stars generally evolve toward the upper right of the Hertzsprung-Russell once they leave the main sequence. That is, they become cooler and brighter, as red giants, as their non-burning cores shrink and heat up.
- High-mass stars explode as supernovae while still in the upper part of the Main Sequence; low-mass stars generally end up as white dwarfs, at the lower left.

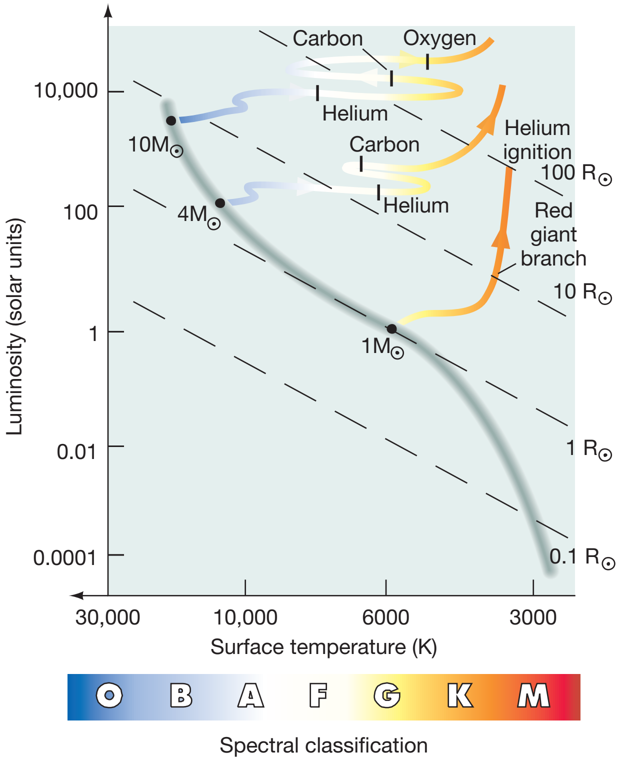
CONCEPT CHECK

Will the Sun ever become a nova?

MA® ANIMATION/VIDEO
Recurrent Nova



◄ **FIGURE 12.15 Nova Matter Ejection** (a) The ejection of material from the star's surface can clearly be seen in this image of Nova Persei, taken some 50 years after it suddenly brightened by a factor of 40,000 in 1901. (b) Nova Cygni, imaged here with a European camera on the *Hubble Space Telescope,* erupted in 1992. At left, more than a year after the blast, a rapidly expanding bubble is seen; at right, 7 months after that, the shell continued to expand and distort. *(Palomar Observatory; ESA)*



▲ **FIGURE 12.16 High-Mass Evolutionary Tracks**
INTERACTIVE Evolutionary tracks for stars of 1, 4, and 10 solar masses. Stars with masses comparable to the mass of the Sun ascend the giant branch almost vertically, whereas higher-mass stars move roughly horizontally across the H–R diagram from the main sequence into the red giant region. Some points are labeled with the element that has just started to fuse in the inner core.

12.4 Evolution of Stars More Massive than the Sun

All stars leaving the main sequence on their way toward the red giant region of the H–R diagram have similar internal structure. Thereafter, however, their evolutionary tracks diverge.

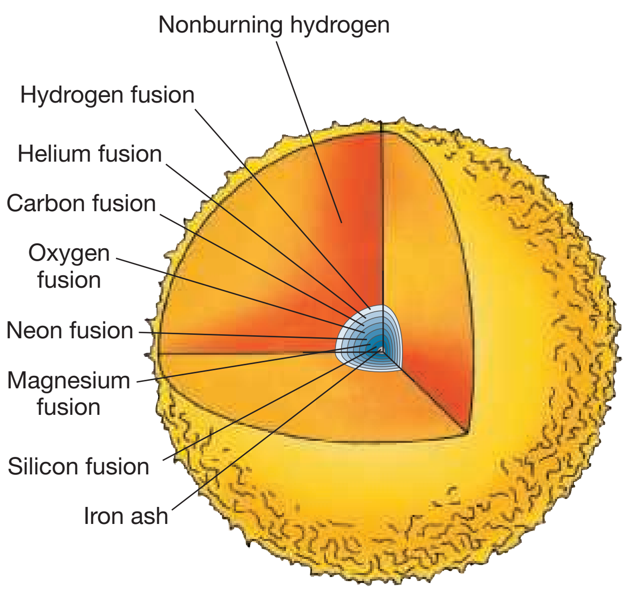
Formation of Heavy Elements

Figure 12.16 compares the post-main-sequence evolution of three stars having masses 1, 4, and 10 times the mass of the Sun. Note the qualitative differences between the solar-mass and higher-mass evolutionary tracks. The solar-mass star ascends the red giant branch almost vertically after leaving the main sequence, its luminosity and radius increasing dramatically while its temperature changes only a little. The higher-mass stars tend to do just the opposite. They loop back and forth across the top of the H–R diagram, their luminosities staying roughly constant as their radii alternately increase and decrease and their surface temperatures fall and rise. The 4- and 10-solar-mass stars do not undergo helium flashes when helium fusion begins, and they do reach core temperatures high enough for helium and carbon to fuse into oxygen.

In the 4-solar-mass star, nuclear burning ceases after the carbon-fusion stage, eventually leading to a carbon–oxygen white dwarf, much as described previously. The fate of the 10-solar-mass star is a little less certain. Depending on how much mass it loses as it evolves (see below), it may also end up as a white dwarf, or it might retain enough mass for fusion to proceed to more massive nuclei. Even higher-mass stars can fuse not just hydrogen, helium, and carbon, but also oxygen, neon, magnesium, silicon, and even heavier elements as their inner cores continue to contract and their central temperatures continue to rise.

Evolution proceeds so rapidly for stars bigger than 10 solar masses that they don't even reach the red giant region before helium fusion begins. Such stars achieve central temperatures of 10^8 K while still quite close to the main sequence. As each element is burned to depletion at the center, the core contracts, heats up, and fusion starts again. A new inner core forms, contracts again, heats again, and so on. The star's evolutionary track continues smoothly across the H–R diagram, seemingly unaffected by each new phase of burning. The star's luminosity stays roughly constant as its radius increases and its surface temperature drops. It swells to become a **red supergiant.**

Figure 12.17 is a cutaway diagram of an evolved high-mass star nearing the end of its red supergiant stage. Note the numerous layers where various nuclei burn. As the temperature increases with depth, the product of each burning stage becomes the fuel for the next. At the relatively cool periphery of the core, hydrogen fuses into helium. In the intermediate layers, shells of helium, carbon, and oxygen burn to form heavier nuclei. Deeper down reside neon, magnesium, silicon, and other heavy nuclei, all produced by nuclear fusion in the layers overlying the nonburning inner core. The inner core itself is composed of iron.



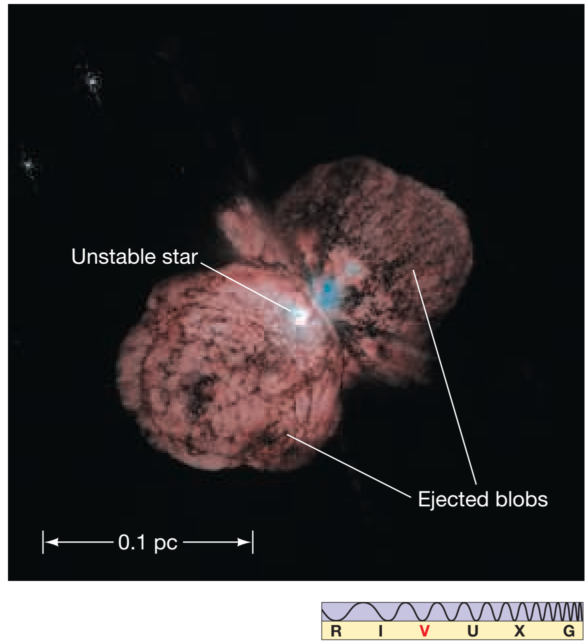
◀ **FIGURE 12.17 Heavy-Element Fusion** Cutaway diagram of the interior of a highly evolved high-mass star shows how the interior resembles the layers of an onion, with shells of progressively heavier elements burning at smaller and smaller radii and at higher and higher temperatures. The core is actually only a few times larger than planet Earth, while the star is hundreds of times larger than the Sun.

Observations of Supergiants

A good example of a post-main-sequence blue supergiant is the bright star Rigel in the constellation Orion. With a radius some 70 times that of the Sun and some 60,000 solar luminosities, Rigel is thought to have had an original mass about 17 times that of the Sun. A strong stellar wind has probably carried away a significant fraction of the star's mass since it formed. Although still near the main sequence, Rigel is probably already fusing helium into carbon in its core.

Astronomers have discovered that, while stars of all spectral types have stellar winds, the highly luminous supergiants have by far the strongest. ∞ *(Sec. 9.3)* Satellite and rocket observations have shown that the winds of some blue supergiants may reach speeds of 3000 km/s and carry off more than 10^{-6} solar masses of material per year. Over the relatively short span of a few million years, these stars can blow a tenth or more of their total mass—a Sun's worth of matter—off into space. During violent outbursts near the end of the star's life, the mass loss rate may exceed 10^{-3} solar masses per year. Figure 12.18 shows a luminous blue variable star called Eta Carinae that is currently displaying this type of behavior. The glowing nebula surrounding the star itself contains up to 3 solar masses of gas shed during this and previous outbursts over the past few hundred years.

Perhaps the best-known red supergiant is Betelgeuse (shown in Figures 10.7 and 10.10), also in Orion and Rigel's rival for the title of brightest star in the constellation. Its luminosity is 10,000 times that of the Sun in visible light and perhaps four times that in the infrared. Astronomers think that Betelgeuse is currently fusing helium into carbon and oxygen in its core, but its eventual fate is uncertain. As best we can tell, the star's mass at formation was between 12 and 17 times the mass of the Sun. However, like Rigel and many other supergiants, Betelgeuse has a strong stellar wind and is known to be surrounded by a huge shell of dust of its own making. This suggests that Betelgeuse has lost a lot of mass since it formed, but just how much remains uncertain.



▲ **FIGURE 12.18 Mass Loss from Supergiants** With an estimated mass of around 100 times the mass of the Sun and a luminosity of 5 million times the solar value, Eta Carinae is one of the most massive and most luminous stars known. This *HST* image shows blobs of ejected material racing away from the star at hundreds of kilometers per second, following a series of explosive outbursts that ejected 2 or 3 solar masses of material into space. *(NASA)*

MA ANIMATION/VIDEO
Light Echo

The End of the Road

Through each period of stability and instability and each new burning stage, the star's central temperature increases, the nuclear reactions speed up, and the newly released energy supports the star for ever shorter periods of time. For example, in round numbers, a star 20 times more massive than the Sun burns hydrogen for 10 million years, helium for 1 million years, carbon for 1000 years, oxygen for 1 year, and silicon for a week. Its iron core grows for less than a day.

Once the inner core begins to change to iron, our high-mass star is in trouble. Nuclear fusion involving iron does not produce energy, because iron nuclei are so tightly bound that energy cannot be extracted by combining them into heavier elements. In effect, iron plays the role of a fire extinguisher, damping the inferno in the stellar core. With the appearance of substantial quantities of iron, the central fires cease for the last time, and the star's internal support begins to dwindle. The star's foundation is destroyed, and its equilibrium is gone forever. Even though the temperature in the iron core has reached several billion kelvins by this stage, the enormous inward gravitational pull of matter ensures catastrophe in the very near future. Gravity overwhelms the pressure of the hot gas, and the star implodes, falling in on itself.

The core temperature rises to nearly 10 billion kelvins. At these temperatures individual photons are energetic enough to split iron into lighter nuclei and then break those lighter nuclei apart until only protons and neutrons remain. This

MA INTERACTIVE
Life and Death of a High-Mass Star

▲ **FIGURE 12.19 Supernova 1987A** A supernova called SN1987A (arrow) was exploding near this nebula (called 30 Doradus) at the moment the photograph at right was taken. The photograph at left is the normal appearance of the star field. (See *Discovery 12-1*.) *(AURA)*

CONCEPT CHECK

Why does the iron core of a high-mass star collapse?

process is known as *photodisintegration*. In less than a second, the collapsing core undoes all the effects of nuclear fusion that occurred during the previous 10 million years. But to split iron and lighter nuclei into smaller pieces requires a lot of energy. After all, this splitting is the opposite of the fusion reactions that generated the star's energy during earlier times. The process thus *absorbs* some of the core's heat energy, reducing the pressure and accelerating the collapse.

Now the core consists entirely of electrons, protons, neutrons, and photons at enormously high densities, and it is still shrinking. As the density continues to rise, the protons and electrons are crushed together, combining to form more neutrons and releasing neutrinos. Even though the central density by this time may exceed, 10^{12} kg/m^3, most of the neutrinos pass through the core as if it weren't there. ∞ *(Sec. 9.5)* They escape into space, carrying away still more energy as they go.

There is nothing to prevent the collapse from continuing all the way to the point at which the neutrons themselves come into contact with each other, at the incredible density of about 10^{15} kg/m^3. At this density, the neutrons in the shrinking core play a role similar in many ways to that of the electrons in a white dwarf. When far apart, they offer little resistance to compression, but when brought into contact, they produce enormous pressures that strongly oppose further contraction. The collapse finally begins to slow. By the time it is actually halted, however, the core has overshot its point of equilibrium and may reach a density as high as 10^{18} kg/m^3 before beginning to reexpand. Like a fast-moving ball hitting a brick wall, the core becomes compressed, stops, then rebounds—with a vengeance!

The events just described do not take long. Only about a second elapses from the start of the collapse to the "bounce" at nuclear densities. Driven by the rebounding core, an enormously energetic shock wave then sweeps outward through the star at high speed, blasting all the overlying layers—including the heavy elements outside the iron inner core—into space. Although the details of how the shock reaches the surface and destroys the star are still uncertain, the end result is not: The star explodes in one of the most energetic events known in the universe (Figure 12.19). This spectacular death rattle of a high-mass star is known as a **core-collapse supernova.**

Our earlier dividing line of 8 solar masses between "low mass" and "high mass" really refers to the mass at the time the carbon core forms. Since very luminous stars often have strong stellar winds, it is possible that main-sequence stars as massive as 10 to 12 times the mass of the Sun may still manage to avoid going supernova. Unfortunately, we do not know exactly how much mass either Rigel or Betelgeuse has lost, so we cannot yet tell whether they are above or below the supernova threshold. Either might explode or instead become a (neon–oxygen) white dwarf, but for now we can't say which. We may just have to wait and see—in a few million years we will know for sure!

Table 12.3 summarizes the possible outcomes of stellar evolution for stars of different masses. For completeness, brown dwarfs—the end product of low-mass protostars unable even to fuse hydrogen in their cores—are included in the list. ∞ *(Sec. 11.4)*

TABLE 12.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	Final State
Less than 0.08	(Hydrogen) brown dwarf
0.08–0.25	Helium white dwarf
0.25–8	Carbon–oxygen white dwarf
8–12 (approx.)*	Neon–oxygen white dwarf
Greater than 12*	Supernova

*Precise numbers depend on the (poorly known) amount of mass lost while the star is on, and after it leaves, the main sequence.

12.5 Supernova Explosions

Novae and Supernovae

Observationally, a *supernova,* like a nova, is a "star" that suddenly increases dramatically in brightness, then slowly dims again, eventually fading from view. However, despite some similarities in their light curves, novae and supernovae are very different phenomena. As we saw in Section 12.3, a nova is a violent explosion on the surface of a white dwarf in a binary system.[2] Supernovae are much more energetic—about a million times brighter than novae—and are driven by very different underlying physical processes. A supernova produces a burst of light billions of times brighter than the Sun, reaching that brightness within just a few hours of the start of the outburst, sometimes rivaling its parent galaxy in brightness (Figure 12.20a). The total amount of electromagnetic energy radiated by a supernova during the few months it takes to brighten and fade away is roughly the same as the Sun will radiate during its *entire* 10^{10}-year lifetime!

Astronomers divide supernovae into two classes. **Type I supernovae** contain very little hydrogen, according to their spectra, and have light curves (see Figure 12.20b) somewhat similar in shape to those of typical novae—a sharp rise in intensity followed by steady, gradual decline. **Type II supernovae** are hydrogen-rich and usually have a characteristic "plateau" in the light curve a few months after the maximum. Observed supernovae are divided roughly evenly between these two categories.

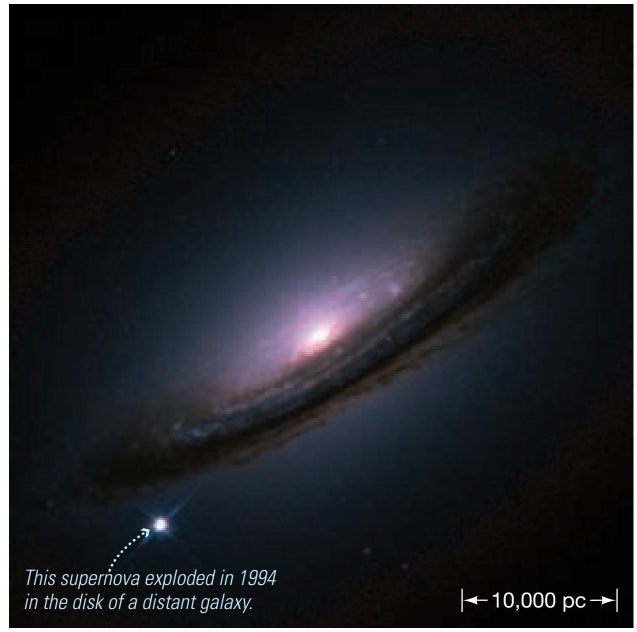
Type I and Type II Supernovae Explained

How do we explain the two types of supernova just described? In fact, we already have half of the answer—the characteristics of Type II supernovae are exactly consistent with the core-collapse supernovae discussed in the previous section. The Type II light curve is in good agreement with computer simulations of a stellar envelope expanding and cooling as it is blown into space by a shock wave sweeping up from below. And since the expanding material consists mainly of unburned hydrogen and helium, it is not surprising that those elements dominate the supernova's spectrum.

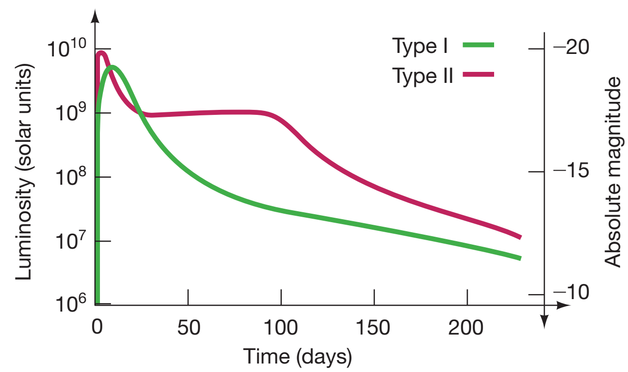
What of Type I supernovae? Is there more than one way for a supernova explosion to occur? The answer is yes. To understand the alternative supernova mechanism, we must reconsider the long-term consequences of the accretion–explosion cycle that causes a nova. A nova explosion ejects matter from a white dwarf's surface, but it does not necessarily expel or burn all the material that has accumulated since the last outburst. In other words, there is a tendency for the dwarf's mass to increase slowly with each new nova cycle. As its mass grows and the internal pressure required to support its weight rises, the white dwarf can enter into a new period of instability—with disastrous consequences.

Recall that a white dwarf is held up by the pressure of electrons that have been squeezed so close together that they have effectively come into contact with one another. However, there is a limit to the mass of a white dwarf, beyond which the electrons cannot support the star against its own gravity. Detailed calculations show that the maximum mass of a white dwarf is about 1.4 solar masses, a mass often called the *Chandrasekhar mass,* after the Indian-American astronomer Subramanyan Chandrasekhar, whose work in theoretical astrophysics earned him a Nobel Prize in Physics in 1983. More recently, in 1999, NASA's latest X-ray

[2]When discussing novae and supernovae, astronomers tend to blur the distinction between the observed event (the sudden appearance and brightening of an object in the sky) and the process responsible for it (a violent explosion in or on a star). The terms can have either meaning, depending on context.

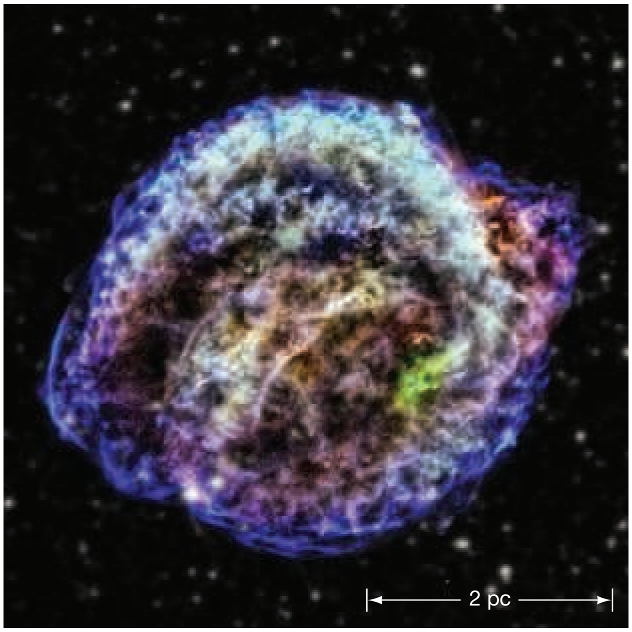


(a)



(b)

▲ **FIGURE 12.20 Supernova Light Curves** (a) The (Type I) supernova SN1994D in the galaxy NGC 4526 was for a time comparable in brightness to the entire galaxy in which it occurred. (b) The light curves of typical Type I and Type II supernovae both show that their maximum luminosities can sometimes reach that of a billion suns, but there are characteristic differences in the decline of luminosity after the initial peak. Type I light curves resemble those of novae (see Figure 12.13c), but the total energy released is much larger. Type II curves have a characteristic plateau during the declining phase.



▲ **FIGURE 12.21 Kepler's Supernova** This X-ray image, captured by the orbiting *Chandra* telescope and released in 2013, shows the aftermath of a titanic stellar explosion that was observed by many people on Earth in 1604. At its peak it was the brightest object in the night sky; it was visible even during the daytime for several weeks. It lies about 6000 pc from Earth. ∞ *(Sec. 1.2)* (CXC)

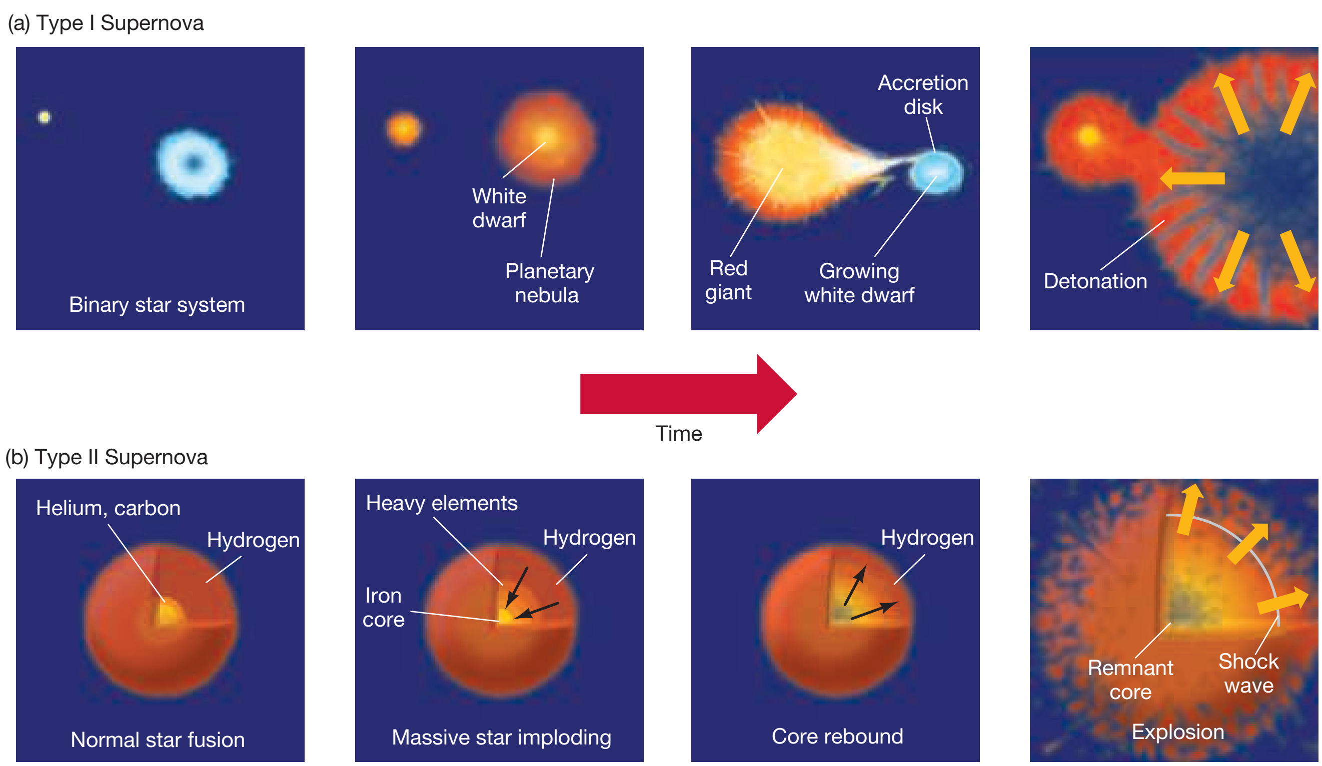
telescope was named *Chandra* in his honor. ∞ *(Sec. 3.5)* Figure 12.21 shows a *Chandra* image of a (relatively) recent Type I supernova.

If an accreting white dwarf exceeds the Chandrasekhar mass, it starts to collapse. Its internal temperature rapidly rises to the point at which carbon can (at last) fuse into heavier elements. Carbon fusion begins everywhere throughout the white dwarf almost simultaneously, and the entire star explodes in a **carbon-detonation supernova**—an event comparable in violence to the core-collapse supernova associated with the death of a high-mass star. In an alternative and (many astronomers think) possibly more common scenario, two white dwarfs in a binary system may collide and merge to form a massive, unstable star. The end result is the same.

The detonation of a carbon white dwarf, the descendant of a *low-mass* star, is a Type I supernova.[3] Because the explosion occurs in a system containing virtually no hydrogen, we can readily see why the supernova spectrum shows little evidence of that element. The light curve is almost entirely due to the radioactive decay of unstable heavy elements produced during the explosion. These explosions have one other important property: Because they all originate in similar systems—white dwarfs whose masses have just exceeded the Chandrasekhar limit—Type I supernovae show remarkably little variation in their properties from one supernova to the next, no matter where (or when) they occur. As we will see in Chapters 15 and 17, this fact, coupled with the huge luminosities involved, make Type I supernovae invaluable tools for mapping out the structure and evolution of the universe on the largest scales.

Figure 12.22 summarizes the processes responsible for the two types of supernovae. Recognize that, despite the similarity in their peak luminosities, Type I

[3]In the jargon of the field, these explosions are technically known as Type Ia supernovae, to distinguish them from the rarer Type Ib and Ic explosions, which are core-collapse events in stars that have lost their hydrogen envelopes.



▲ **FIGURE 12.22 Two Types of Supernova** Type I and Type II supernovae have different causes. These sequences depict the evolutionary history of each type. (a) A Type I supernova usually results when a carbon-rich white dwarf pulls matter onto itself from a nearby red giant or main-sequence companion. (b) A Type II supernova occurs when the core of a high-mass star collapses and then rebounds in a catastrophic explosion.

and Type II supernovae are unrelated to one another. They occur in stars of very different types, under very different circumstances. All high-mass stars become Type II (core-collapse) supernovae, but only a tiny fraction of low-mass stars evolve into white dwarfs that ultimately explode as Type I (carbon-detonation) supernovae. However, there are far more low-mass stars than high-mass stars, resulting in the remarkable coincidence that the two types of supernova occur at roughly the same rate.

CONCEPT CHECK

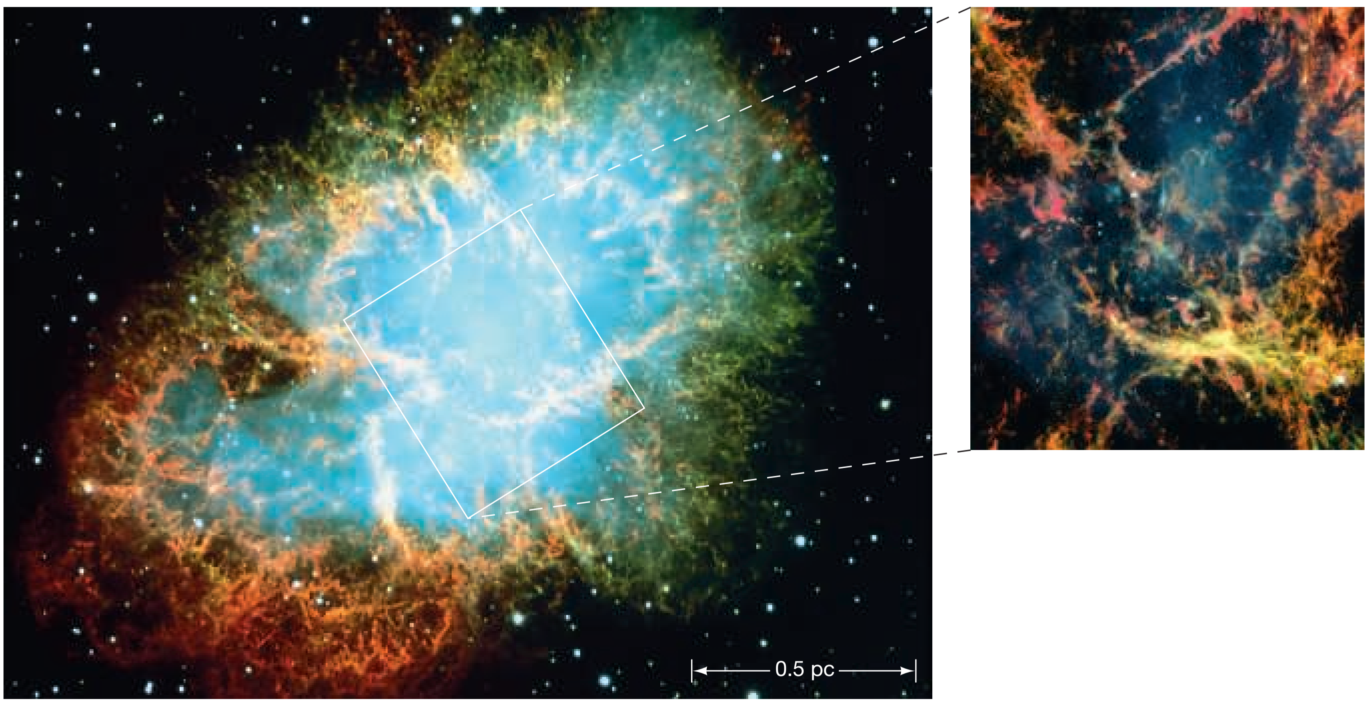
How did astronomers know, even before the mechanisms were understood, that there were at least two distinct physical processes at work in creating supernovae?

Supernova Remnants

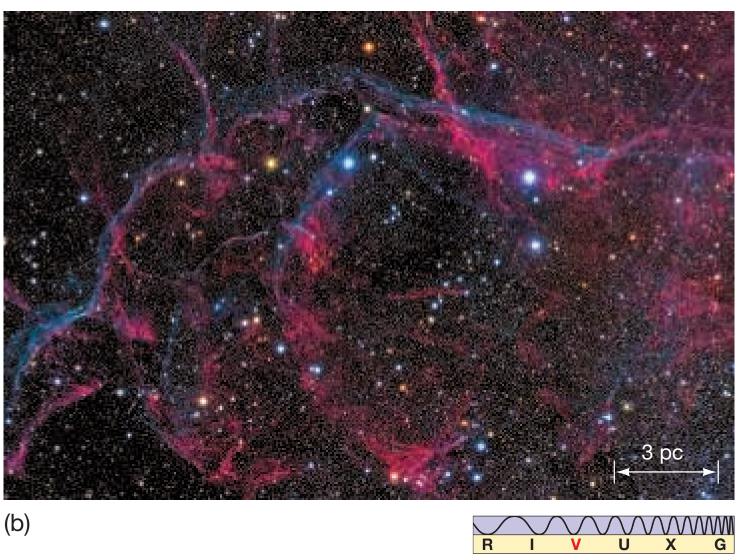
We have plenty of evidence that supernovae have occurred in our Galaxy. Occasionally, the supernova explosions are visible from Earth. In other cases, we can detect their glowing remains, or **supernova remnants.** One of the best-studied supernova remnants is the Crab Nebula (Figure 12.23a). Its brightness has

MA ANIMATION/VIDEO
Supernova Explosions

MA INTERACTIVE
Supernova Remnant Cassiopeia A



(a)



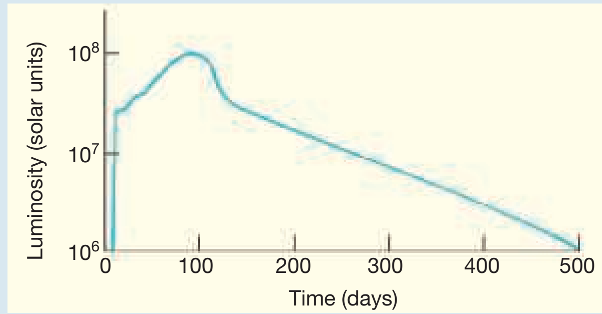
(b)

◄ **FIGURE 12.23 Supernova Remnants INTERACTIVE** (a) This remnant of an ancient Type II supernova is called the Crab Nebula. It resides about 1800 pc from Earth, and its debris is scattered over a region about 2 pc across. The main image was taken with the Very Large Telescope of the European Southern Observatory in Chile, the inset by the *Hubble* telescope in orbit. (b) The glowing gases of the Vela supernova remnant are spread across 6° of the sky. *(ESO; NASA; ESO)*

12.1 DISCOVERY

Supernova 1987A

Although there have been no observable supernovae in our own Galaxy since the invention of the telescope, astronomers were treated to the next best thing in 1987 when a 15-solar mass B-type supergiant exploded in the Large Magellanic Cloud (LMC), a small satellite galaxy orbiting our own (see Section 15.1). For a few weeks the Type II supernova SN1987A, shown in Figure 12.19, outshone all the other stars in the LMC combined. Because the LMC is relatively close to Earth and the explosion was detected soon after it occurred, SN1987A provided astronomers with a wealth of detailed information on supernovae, allowing them to make key comparisons between theoretical models and observational reality. By and large, the theory of stellar evolution has held up very well. Still, SN1987A did hold a few surprises.



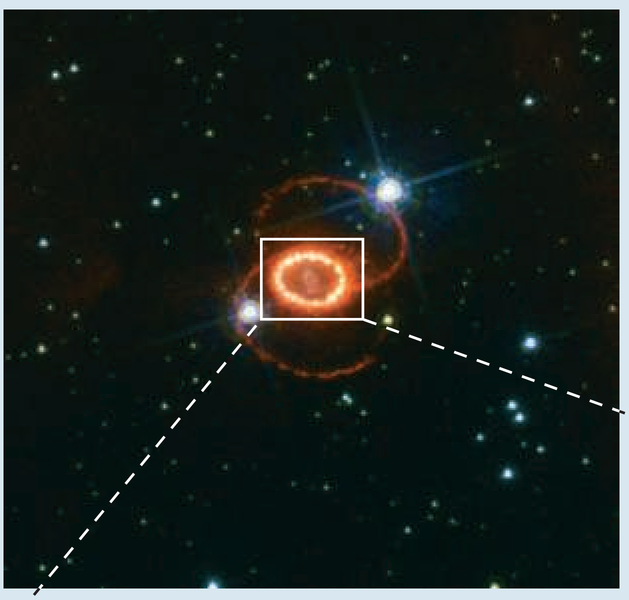
The light curve of SN1987A, shown at right, differed somewhat from the "standard" Type II shape (Figure 12.20). The peak brightness was only about 1/10 the standard value and occurred much later than expected. These differences stemmed from the fact that the parent star's envelope was deficient in heavy elements, significantly altering its evolutionary track. As a result, the star was a (relatively small) blue supergiant, at the top right of the H-R diagram with a surface temperature of around 20,000 K, when the rapid chain of events leading to the supernova occurred.

Because the parent star was small and quite tightly bound by gravity, a lot of the energy produced in the explosion was used in expanding SN1987A's stellar envelope, so far less was left over to be radiated into space. Thus the luminosity during the first few months was lower than expected, and the early peak evident in Figure 12.20 did not occur. The peak in the SN1987A light curve at about 80 days actually corresponds to the "plateau" in the Type II light curve in Figure 12.20.

About 20 hours before the supernova was detected optically, underground detectors in Japan and the United States recorded a brief (13-second) burst of neutrinos. The neutrinos preceded the light because they escaped during the collapse, whereas the first light of the explosion was emitted only after the supernova shock had plowed through the body of the star to the surface. Theoretical models, consistent with these observations, suggest that many tens of thousands of times more energy was emitted in the form of neutrinos than in any other form. Detection of this neutrino pulse was a brilliant confirmation of theory and may well herald a new age of astronomy. For the first time, astronomers received information from beyond the solar system by means outside the electromagnetic spectrum.

The accompanying photographs show the barely resolved remnant of SN1987A (at the center of each image) surrounded by a much larger shell of glowing gas (in yellow). The progenitor star expelled this shell during its red giant phase, some 40,000 years before the explosion. The image we see results from the flash of ultraviolet light from the supernova hitting the ring and causing it to glow brightly. The insets at the bottom show supernova debris moving outward toward the ring at nearly 3000 km/s. The fastest-moving ejecta have already reached the ring, forming the glowing regions that now surround the supernova remnant. The main image also revealed two additional faint rings that might be caused by radiation sweeping across an hourglass-shaped bubble of gas, itself perhaps the result of a nonspherical "bipolar" stellar wind from the progenitor star before the supernova occurred.

Buoyed by the success of stellar-evolution theory astronomers eagerly await further developments in the story of this remarkable object.

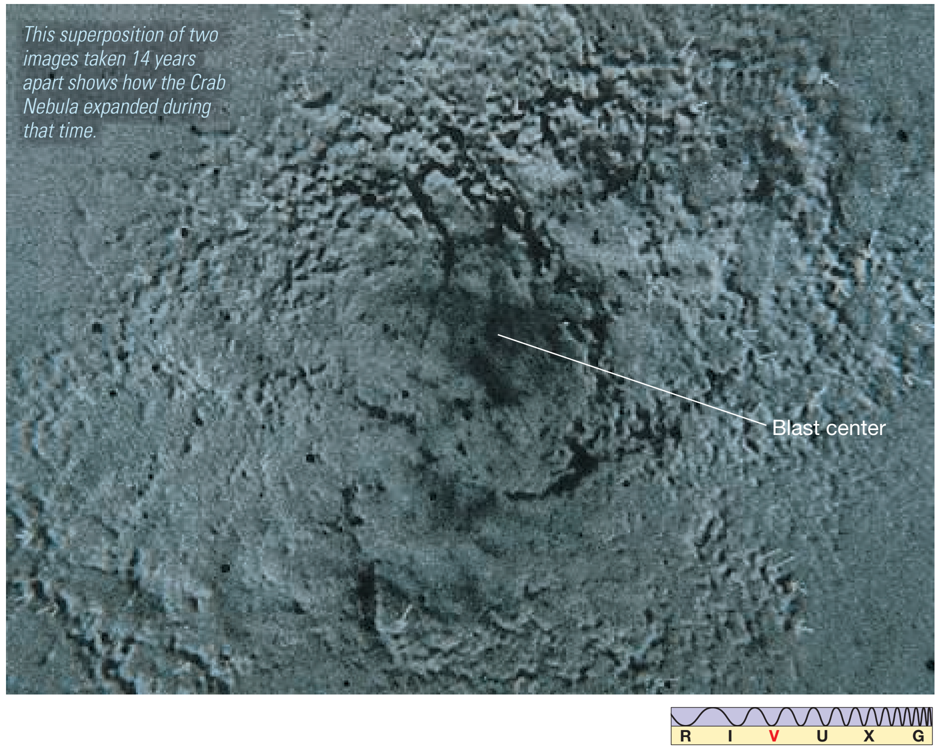


(NASA)

MA ANIMATION/VIDEO
Shockwaves Hit the Ring Around Supernova 1987A

greatly dimmed now, but the original explosion in the year A.D. 1054 was so brilliant that it is prominently recorded in the manuscripts of Chinese and Middle Eastern astronomers. For nearly a month, this exploded star reportedly could be seen in broad daylight. Even today, the knots and filaments give a strong indication of past violence. The nebula—the envelope of the high-mass star that exploded to create this Type II supernova—is still expanding into space at a speed of several thousand kilometers per second. Figure 12.24 illustrates this motion by combining a positive image of the Crab taken in 1960 with a negative image taken in 1974. If the gas were not moving, the positive and negative images would overlap perfectly, but they do not. The gas moved outward in the intervening 14 years. Tracing the motion backward in time, astronomers have found that the explosion must have occurred about nine centuries ago, consistent with the Chinese and Middle Eastern observations.

Figure 12.23b shows another example (also of Type II). The expansion velocity of the Vela supernova remnant implies that its central star exploded around 9000 B.C. This remnant lies only 500 pc from Earth. Given its proximity, it may have been as bright as the Moon for several months. See also Figure 3.29 for an X-ray image of a nearby supernova remnant.



▲ **FIGURE 12.24 The Crab in Motion** Positive and negative photographs of the Crab Nebula taken 14 years apart do not superimpose exactly, indicating that the gaseous filaments are still moving away from the site of the explosion. The positive image in white was taken first, and the black (negative) filaments were overlaid later—hence the black (but still glowing) outlying debris is farther from the center of the blast. The scale is roughly the same as in Figure 12.23(a). *(Harvard College Observatory)*

Although hundreds of supernovae have been observed in other galaxies during the 20th century, no one using modern equipment has ever observed one in our own Galaxy. (See *Discovery 12-1* for a discussion of a recent supernova in a galaxy very close to our own.) A viewable Milky Way star has not exploded since Galileo first turned his telescope to the heavens almost four centuries ago. Based on stellar evolutionary theory, astronomers estimate that an observable supernova ought to occur in our Galaxy every 100 years or so. Our local neighborhood seems long overdue for one. Unless stars explode much less frequently than predicted by theory, we should be treated to a (relatively) nearby version of nature's most spectacular cosmic event any day now.

DATA POINTS

Novae and Supernovae

Two-thirds of students had difficulty distinguishing novae and the different kinds of supernovae. Some points to remember:

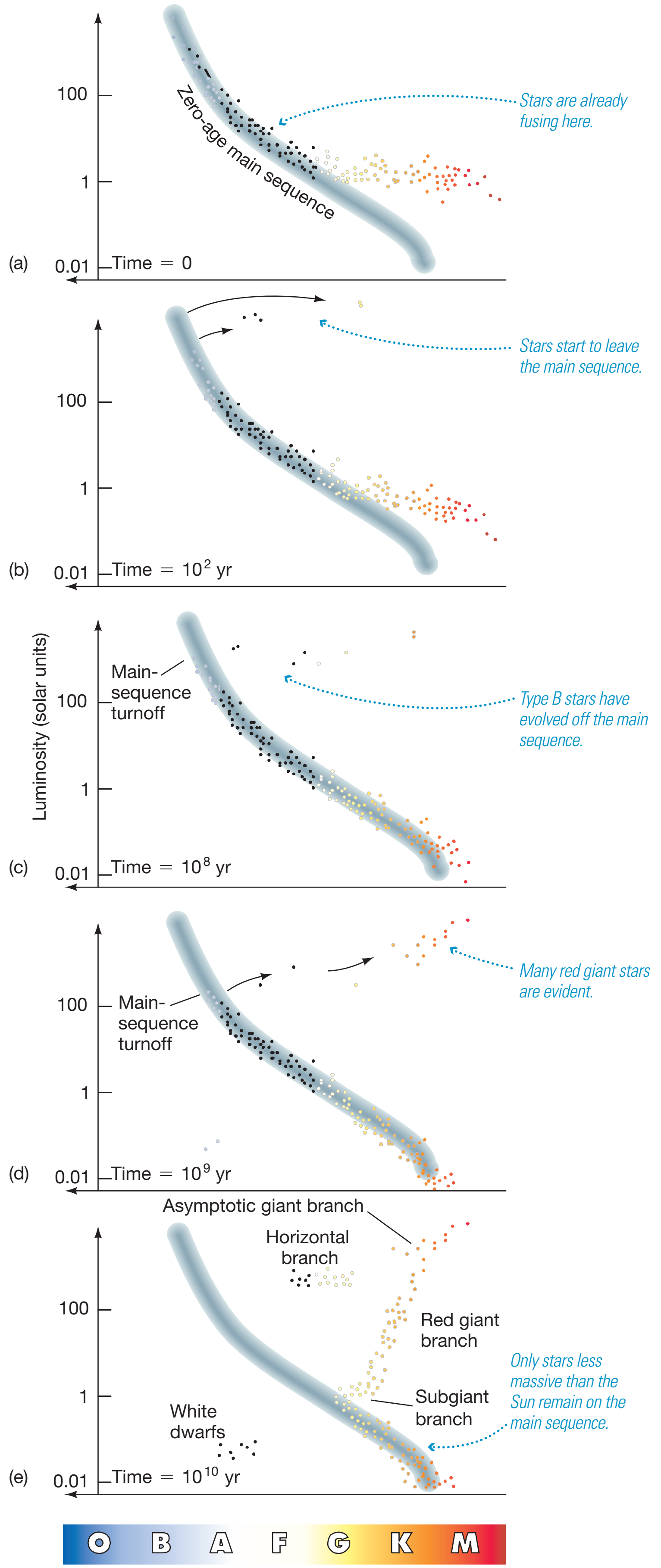
- Supernovae are millions of times brighter than novae.
- Novae are thermonuclear detonations on the surfaces of white dwarf stars. They are violent, but do not destroy the star on which they occur.
- A Type I supernova is a detonation involving an entire white dwarf that has exceeded its maximum stable mass. The explosion likely leaves no remnant behind.
- A Type II supernova results from the runaway collapse of the core of a massive star; it probably leaves a neutron star or black hole remnant behind.

Formation of the Heavy Elements

From the point of view of life on Earth, probably the most important aspect of stellar evolution is its role in creating, and then dispersing, the heavy elements out of which both our planet and our bodies are made. Since the 1950s, astronomers have come to realize that all of the hydrogen and most of the helium in the universe are *primordial*—that is, they date back to the very earliest times, long before the first stars formed (see Section 17.6). All other elements (and, in particular, virtually everything we see around us on Earth) formed later, in stars.

We have already seen how heavy elements are created from light ones by nuclear fusion. This is the basic process that powers all stars. Hydrogen fuses to helium, then helium to carbon and oxygen. Subsequently, in high-mass stars, carbon and oxygen can fuse to form still heavier elements. Neon, magnesium, sulfur, silicon—in fact, elements up to and including iron—are created in turn by fusion reactions in the cores of the most massive stars.

However, fusion stops at iron. The fact that iron nuclei will not fuse to release energy and create more massive nuclei is the basic underlying cause of Type II supernovae. How then were even heavier elements, such as copper, lead, gold, and uranium, formed? As mentioned in Section 12.3, some of these elements were formed during the late red giant stages of low-mass stars via



reactions involving neutrons. Similar reactions occur in supernovae too, where neutrons and protons, produced when some nuclei are ripped apart by the almost unimaginable violence of the blast, are crammed into other nuclei, creating heavy elements that cannot have formed by any other means. Many of the heaviest elements were formed *after* their parent stars had already died, even as the debris from the explosion signaling the stars' deaths was hurled into interstellar space. In this way stellar evolution steadily enriches the composition of each new generation of stars.

Although no one has ever observed directly the formation of heavy nuclei in stars, astronomers are confident that the chain of events just described really occurs. When nuclear reaction rates (determined from laboratory experiments) are incorporated into detailed computer models of stars and supernovae, the results agree very well, point by point, with the composition of the universe inferred from analysis of meteorites and spectroscopic studies of planets, stars, and the interstellar medium. The reasoning is indirect, but the agreement between theory and observation is so striking that most astronomers regard it as strong evidence supporting the entire theory of stellar evolution.

12.6 Observing Stellar Evolution in Star Clusters

Star clusters provide excellent test sites for the theory of stellar evolution. Every star in a given cluster formed at nearly the same time, from the same interstellar cloud, with virtually the same composition. ∞ *(Sec. 11.6)* Only the mass varies from one star to another. This uniformity allows us to check the accuracy of our theoretical models in a very straightforward way. Having studied in some detail the evolutionary tracks of individual stars, let us now consider how their collective appearance changes in time.

We begin our study shortly after the cluster's formation, with the high-mass stars already fully formed and burning steadily on the upper main sequence and lower-mass stars just beginning to arrive on the main sequence (Figure 12.25a). The appearance of the cluster at this early stage is dominated by its most massive stars—the bright blue supergiants.

Figure 12.25(b) shows our cluster's H–R diagram after 10 million years. The most massive O-type stars have evolved off the main sequence. Most have already exploded and vanished, but one or two may still be visible as supergiants traversing the top of the diagram. The remaining cluster stars are largely unchanged in appearance.

◄ **FIGURE 12.25 Cluster Evolution on the H–R Diagram** (a) Initially, stars on the upper main sequence are already burning steadily while the lower main sequence is still forming. (b) At 10^7 years, O-type stars have already left the main sequence, and a few red giants are visible. (c) By 10^8 years, more red giants are visible, and the lower main sequence is almost fully formed. (d) At 10^9 years, the subgiant and red giant branches are just becoming evident, and the formation of the lower main sequence is complete. (e) At 10^{10} years, the cluster's subgiant, red giant, horizontal, and asymptotic giant branches are all discernible, and many white dwarfs have now formed.

The cluster's H–R diagram has a slightly shortened main sequence. Figure 12.26 shows the twin open clusters h and (the Greek letter chi) Persei, along with their observed H–R diagram. Comparing Figure 12.26(b) with Figure 12.25(b), astronomers estimate the age of this double cluster to be about 10 million years.

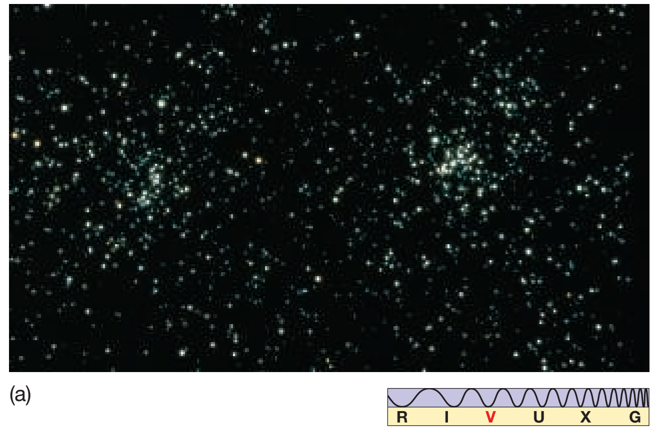
After 100 million years (Figure 12.25c), stars brighter than type B5 or so (about 4 to 5 solar masses) have left the main sequence, and a few more supergiants are visible. By this time most of the cluster's low-mass stars have finally arrived on the main sequence, although the dimmest M-type stars may still be in their contraction phase. The appearance of the cluster is now dominated by bright B-type stars and brighter supergiants.

At any time during the evolution, the cluster's original main sequence is intact up to some well-defined stellar mass, corresponding to the stars that are just leaving the main sequence at that instant. We can imagine the main sequence being "peeled away" from the top down, with fainter and fainter stars turning off and heading for the giant branch as time goes on. Astronomers refer to the high-luminosity end of the observed main sequence as the **main-sequence turnoff.** The mass of the star that is just evolving off the main sequence at any moment is known as the *turnoff mass*. Knowing the turnoff mass is equivalent to knowing the age of the cluster—stars less massive than the turnoff are still on the main sequence, while more massive stars have already evolved into something else.

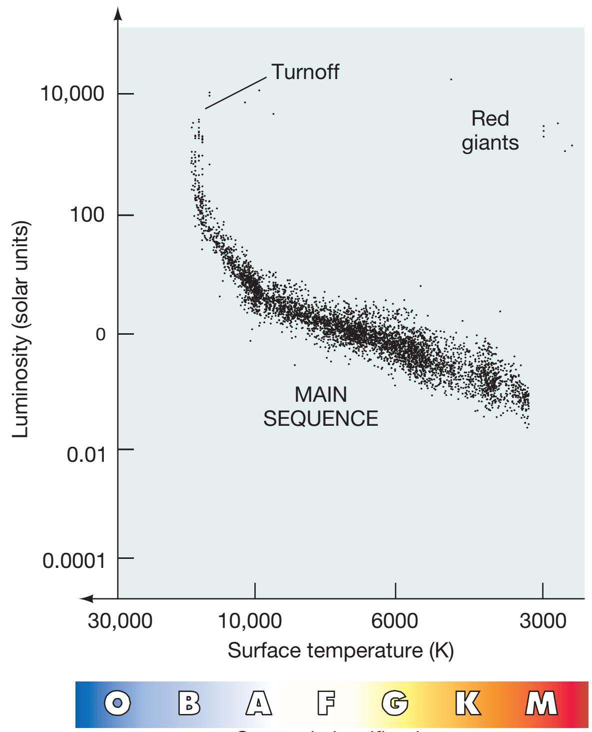
At 1 billion years (Figure 12.25d) the main-sequence turnoff mass is around 2 solar masses, corresponding roughly to spectral type A2. The subgiant and giant branches associated with the evolution of low-mass stars are just becoming apparent, and the formation of the lower main sequence is now complete. In addition, the first white dwarfs have just appeared, although they are often too faint to be observed at the distances of most clusters. Figure 12.27 shows the Hyades open cluster and its H–R diagram. The H–R diagram appears to lie between Figures 12.25 (c) and (d). More careful measurements yield a cluster age of about 600 million years.

At 10 billion years, the turnoff point has reached solar-mass stars, of spectral type G2. The subgiant and giant branches are now clearly discernible in the H–R diagram (Figure 12.25e), and the horizontal branch appears as a distinct region. Many white dwarfs are also present in the cluster. Figure 12.28 shows a composite H–R diagram for several globular clusters in our Galaxy. The various evolutionary stages predicted by theory are all clearly visible in this figure, although the individual points are shifted somewhat to the left relative to our previous H–R diagrams because of differences in composition between stars like the Sun and stars in globular clusters. (Globular cluster stars tend to be hotter than solar-type stars of the same mass.) The clusters represented in Figure 12.28(b) are quite deficient in heavy elements compared with the Sun. Figure 12.28(a) shows a *Hubble* image of the globular cluster M80, which has a similarly low concentration of heavy elements—only about 2 percent the solar value—and whose H–R diagram looks qualitatively very similar to Figure 12.28.

By carefully adjusting their theoretical models until the main sequence, subgiant, red giant, and horizontal branches are all well matched, astronomers find that this diagram corresponds to a cluster age of roughly 12 billion years, a little older than the hypothetical cluster in Figure 12.25(e). The deficiency of heavy elements is consistent with these clusters being among the first objects to form in our Galaxy (see Section 12.7). In fact, globular cluster ages determined this way show a remarkably small spread. Most of the globular clusters in our Galaxy formed between about 10 and 12 billion years ago.

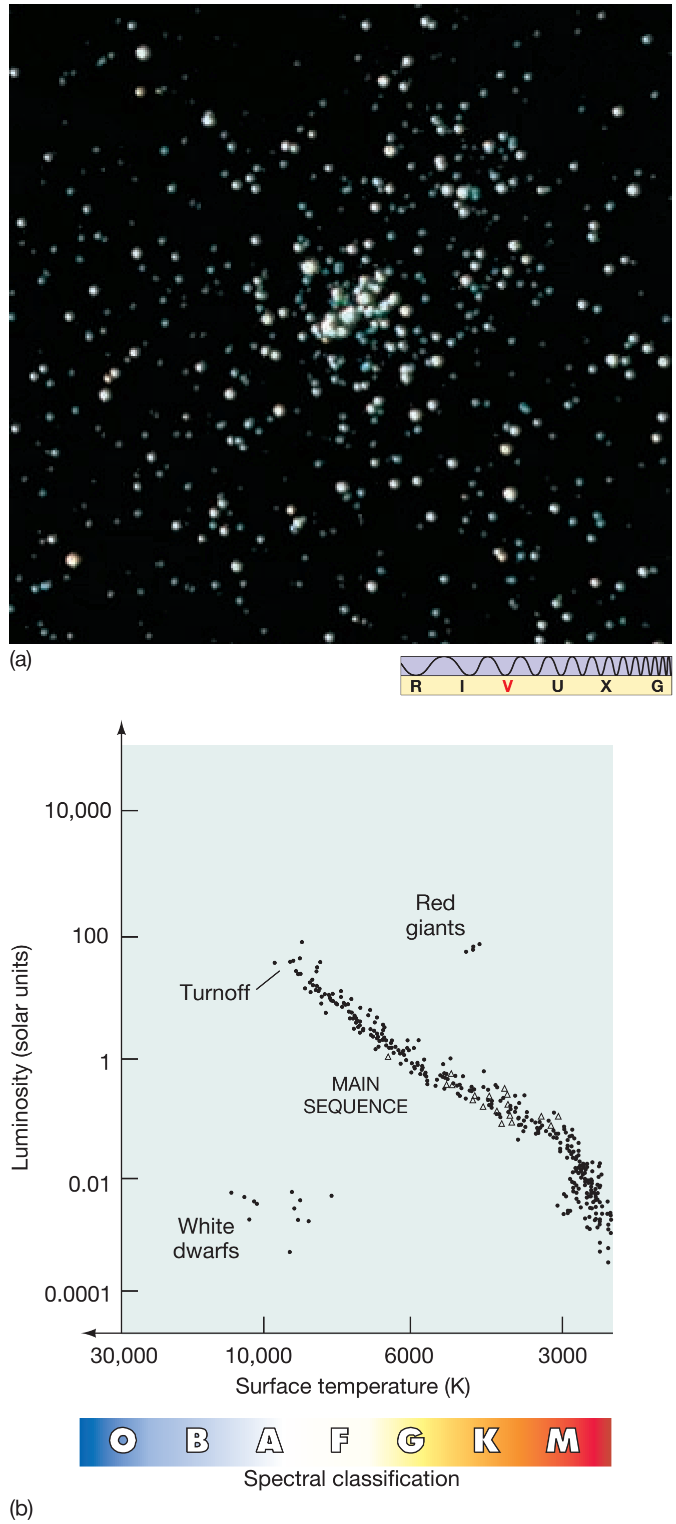


(a)

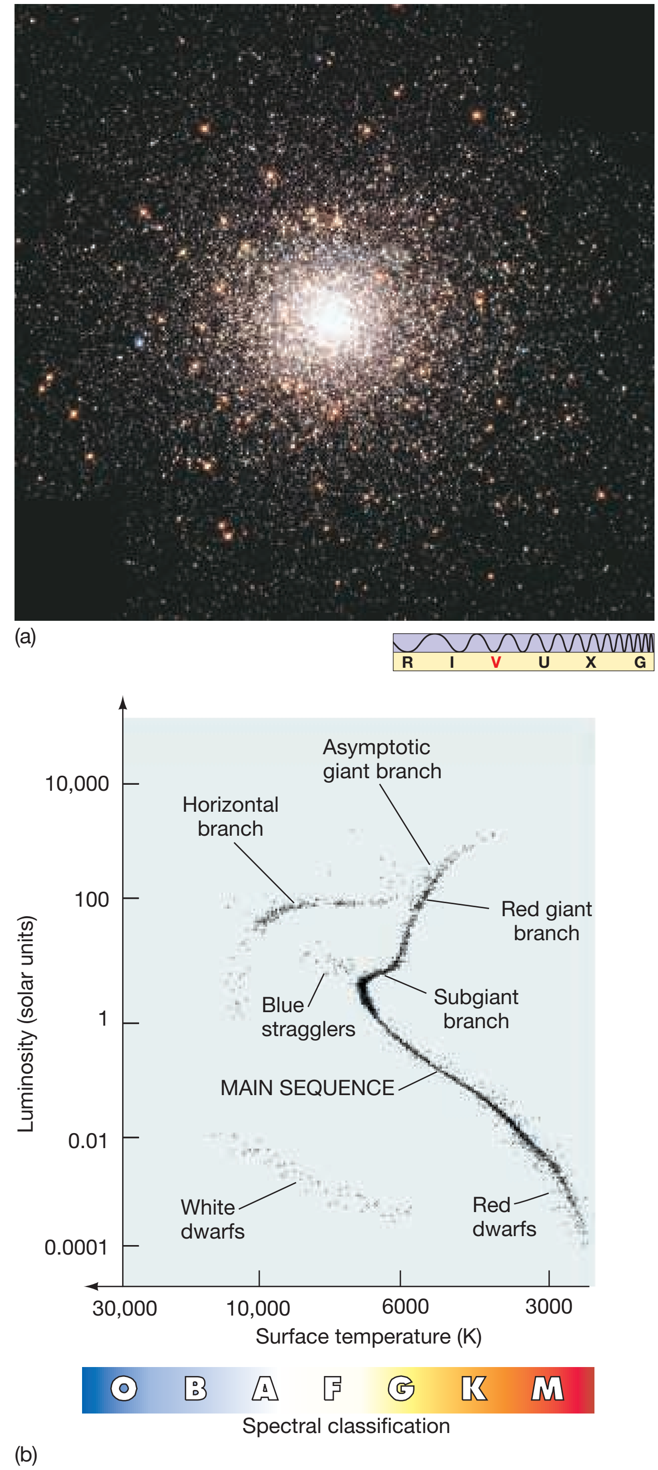


(b)

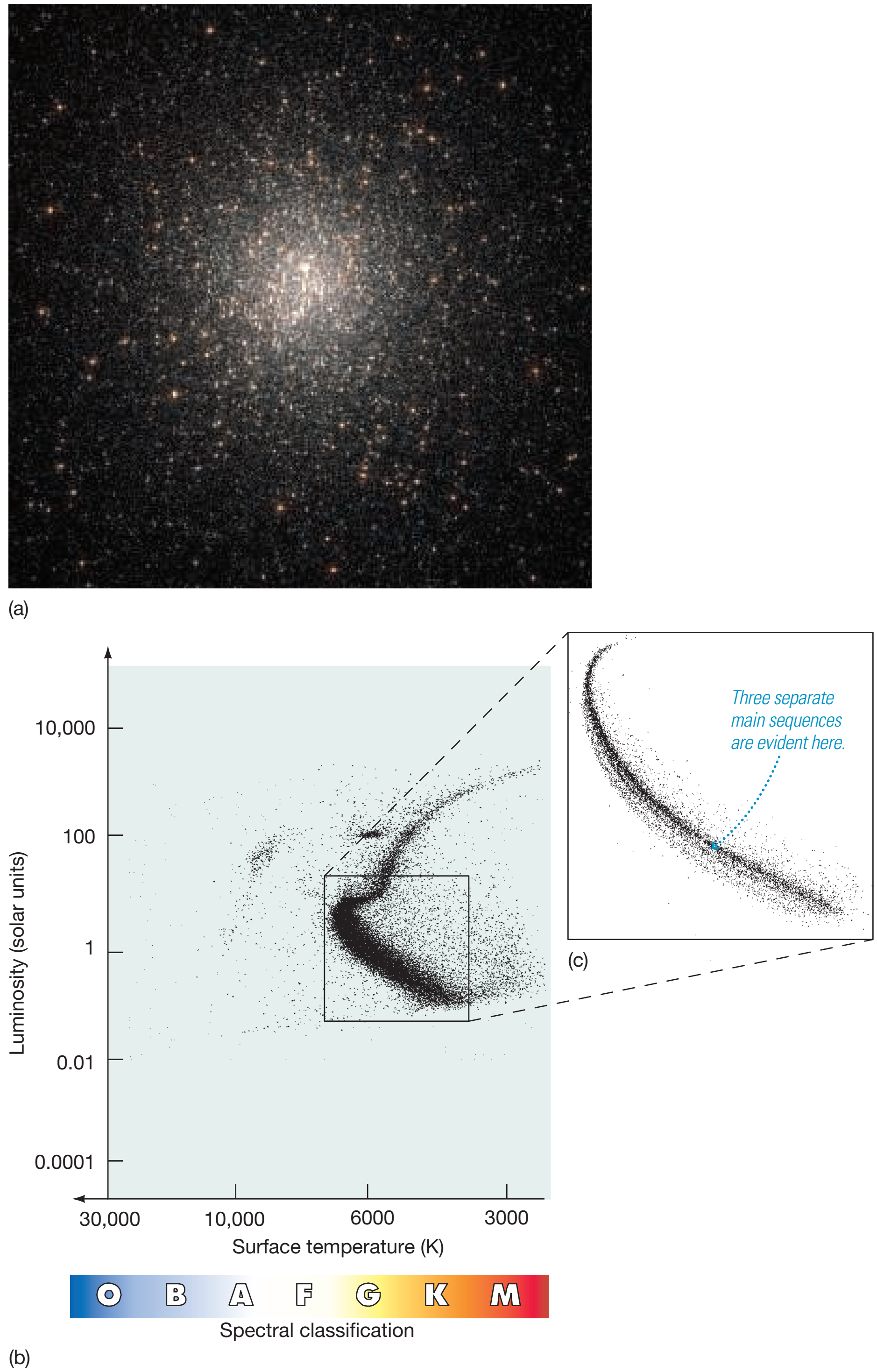
▲ **FIGURE 12.26 Newborn Cluster H–R Diagram** (a) The "double cluster" h and χ Persei, two open clusters that apparently formed at the same time. (b) The H–R diagram of the pair indicates that the stars are very young—probably only 10–15 million years old. Even so, the most massive stars have already left the main sequence. *(NOAO; data from T. Currie)*



▲ **FIGURE 12.27 Young Cluster H–R Diagram** (a) The Hyades cluster, a relatively young group of stars visible to the naked eye, is found 46 pc away in the constellation Taurus. (b) The H–R diagram for this cluster is cut off at about spectral type A, implying an age of about 600 million years. A few massive stars have already become white dwarfs. *(NOAO)*



▲ **FIGURE 12.28 Old Cluster H–R Diagram** (a) The globular cluster M80, which lies some 8 kpc from Earth. (b) Combined H–R diagram, based on ground- and space-based observations, for several globular clusters similar in overall composition to M80. Fitting the main-sequence turnoff and the giant and horizontal branches to theoretical models implies an age of about 12 billion years, making these clusters among the oldest known objects in the Milky Way Galaxy. *(NASA; data courtesy of William E. Harris)*



▶ **FIGURE 12.29 Multiple Stellar Generations** The ground-based H–R diagram (b) of the globular cluster NGC 2808 (a) shows an apparently normal main sequence, but more precise observations from *HST* (c) reveal that the main sequence is actually made up of three distinct sequences (as noted), increasing in helium content from right to left. These observations imply multiple generations of star formation shortly after the cluster formed, but no theory can yet explain just how this occurred. *(NASA)*

The objects labeled as *blue stragglers* in Figure 12.28(b) appear at first sight to contradict the theory just described. They lie on the main sequence, but above the turnoff, suggesting that they should have evolved into white dwarfs long ago, given the cluster's age of 12 billion years. Blue stragglers are observed in many star clusters. They are main-sequence stars, but they did not form when the cluster did. Instead, they formed much more recently, through *mergers* of lower-mass stars—so recently, in fact, that they have not yet had time to evolve into giants. In some cases, the mergers were probably the result of stellar evolution in binary systems, as the component stars evolved, grew, and came into contact. In others, the mergers are thought to be the result of actual *collisions* between stars. The dense central cores of globular clusters—with a million or more times as many stars per unit volume as are found in the neighborhood of the Sun—are among the few places in the entire universe where stellar collisions are likely to occur.

High-precision observations from *HST* have revealed a new, and as yet unresolved, mystery about globular clusters that may yet force astronomers to change significantly their views on how massive star clusters form. Figure 12.29 presents the H–R diagram for the cluster NGC 2808, showing (in the inset) what appear to be *three* distinct main sequences, undetected in earlier ground-based observations. The stars in the three sequences contain different amounts of helium, carbon, and nitrogen and are thought to be the result of multiple episodes of star formation occurring over the course of about 100 million years. Models suggest that the two more helium-rich generations formed from gas enriched by stellar evolution in the first-generation stars, but astronomers do not know how this could have occurred in the time available. Whatever happened, it seems to have been a common phenomenon, as high-resolution studies of many globular clusters now reveal similar multiple populations. Indeed, some observers would go so far as to claim that multiple stellar populations are the norm in the Galactic globular cluster population.

12.7 The Cycle of Stellar Evolution

PROCESS OF SCIENCE CHECK

Why are observations of star clusters so important to the theory of stellar evolution?

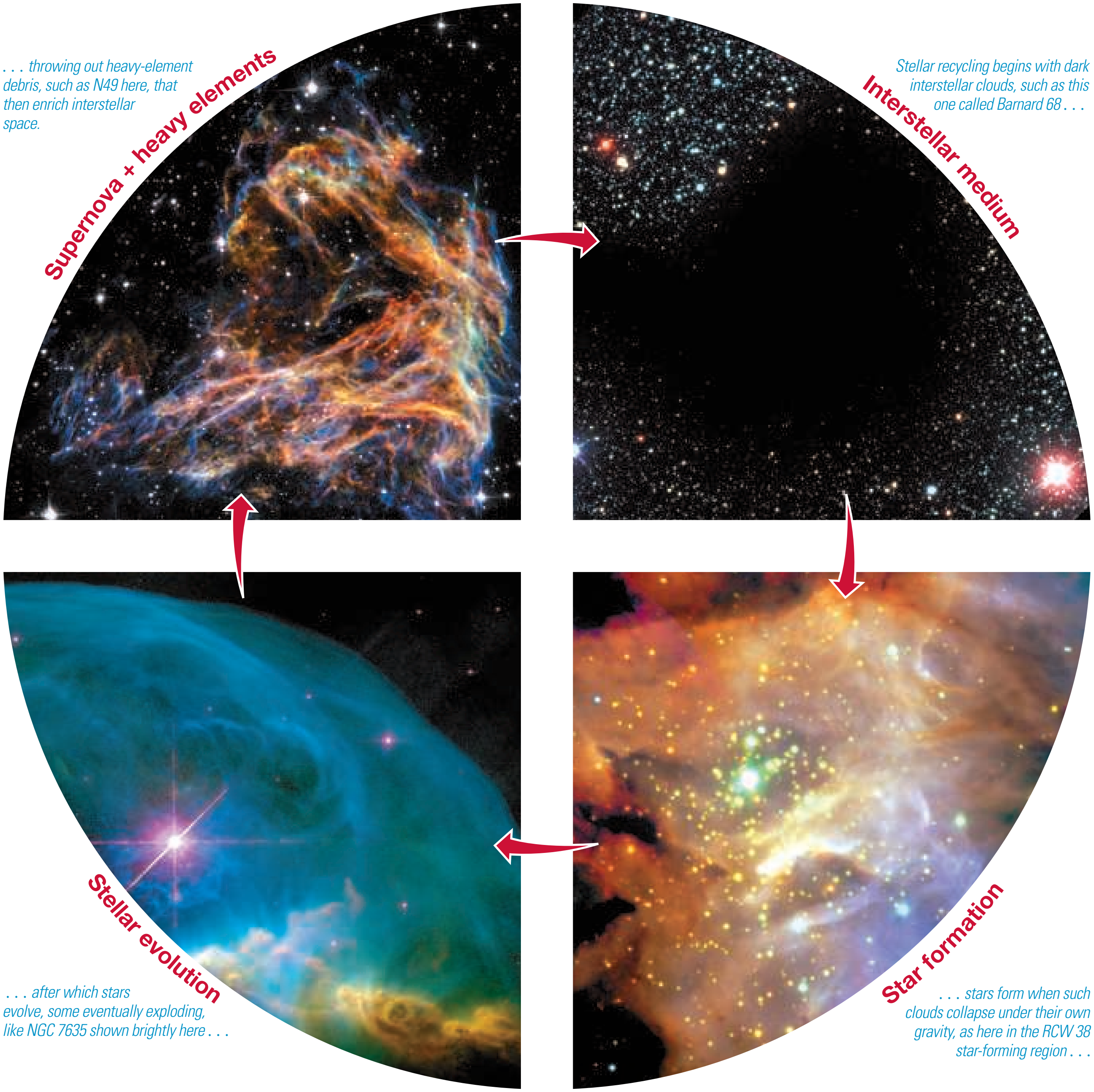
The theory of stellar evolution outlined in this chapter can naturally account for the observed differences in the abundances of heavy elements between the old globular-cluster stars and stars now forming in our Galaxy. Even though an evolved star continuously creates new heavy elements in its interior, changes in the star's composition are confined largely to the core, and the star's spectrum may give little indication of the events within. Only at the end of the star's life are its newly created elements released and scattered into space.

Thus the spectra of the *youngest* stars show the *most* heavy elements because each new generation of stars increases the concentration of these elements in the interstellar clouds from which the next generation forms. Accordingly, the photosphere of a recently formed star contains a much greater abundance of heavy elements than that of a star formed long ago. Knowledge of stellar evolution allows astronomers to estimate the ages of stars from purely spectroscopic studies, even when the stars are isolated and are not members of any cluster.

We have now seen all the ingredients that make up the complete cycle of star formation and evolution. Let us now briefly summarize that process, which is illustrated in Figure 12.30.

1. Stars form when part of an interstellar cloud is compressed beyond the point at which it can support itself against its own gravity. The cloud collapses and fragments, forming a cluster of stars. The hottest stars heat and ionize the surrounding gas, sending shock waves through the surrounding cloud, modifying the formation of lower-mass stars, and possibly triggering new rounds of star formation. ∞ *(Secs. 11.2, 11.3)*
2. Within the cluster, stars evolve. The most massive stars evolve fastest, creating heavy elements in their cores and spewing them forth into the interstellar medium in supernova explosions. Low-mass stars evolve more slowly, but they too create heavy elements and contribute significantly to the "seeding" of interstellar space when they shed their envelopes as planetary nebulae. Roughly speaking, low-mass stars created most of the carbon, nitrogen, and oxygen that make life on Earth possible. High-mass stars produced the iron and silicon that make up Earth itself, as well as the heavier elements on which much of our technology is based.
3. The creation and explosive dispersal of new heavy elements are accompanied by further shock waves. The passage of these shock waves through the interstellar medium simultaneously enriches the medium and compresses it into further star formation. Each generation of stars increases the concentration of heavy elements in the interstellar clouds from which the next generation forms. As a result, recently formed stars contain a much greater abundance of heavy elements than stars that formed long ago.

In this way, although some material is used up in each cycle—turned into energy or locked up in stars less massive than the Sun (most of which have not yet left the main sequence)—the Galaxy continuously recycles its matter. Each new round of formation creates stars containing more heavy elements than the preceding generation had. From the old globular clusters, which are observed to be deficient in heavy elements relative to the Sun, to the young open clusters, which contain much larger amounts of these elements, we observe this enrichment process in action. Our Sun is the product of many such cycles. We ourselves are another. Without the heavy elements synthesized in the hearts of stars, life on Earth would not exist.



▲ **FIGURE 12.30 Stellar Recycling** **INTERACTIVE** The cycle of star formation and evolution continuously replenishes the Galaxy with new heavy elements and provides the driving force for the creation of new generations of stars. Clockwise from the top are an interstellar cloud (Barnard 68), a star-forming region in our Galaxy (RCW 38), a massive star ejecting a "bubble" and about to explode (NGC 7635), and a supernova remnant and its heavy-element debris (N49). *(ESO; NASA)*

Stellar evolution is one of the great success stories of astrophysics. Like all good scientific theories, it makes definite, testable predictions about the universe, at the same time remaining flexible enough to incorporate new discoveries as they occur. Theory and observation have advanced hand in hand. At the start of the 20th century, many scientists despaired of ever knowing the compositions of the stars, let alone why they shine and how they change. Today, the theory of stellar evolution is a cornerstone of modern astronomy.

CONCEPT CHECK

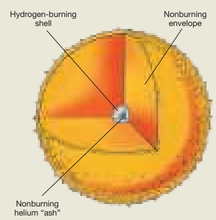
Why is stellar evolution important to life on Earth?

THE BIG QUESTION

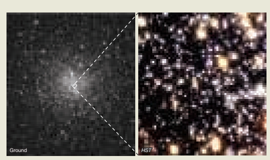
If stars like the Sun end their lives quiescently and similarly, why do their scattered remnants look so different on the sky? Planetary nebulae display all sorts of weird shapes and sizes, some with rings and spheres, others with loops and jets. What causes these dissimilar structures? Are they somehow intrinsic to the stars themselves, or are they due to the complex environments through which dying stars expel their contents into interstellar space?

CHAPTER REVIEW

SUMMARY



LO1 Stars spend most of their lives on the main sequence, in the **core hydrogen-burning** (stage 7; p. 332) phase of stellar evolution. Stars leave the main sequence when the hydrogen in their cores is exhausted. With no internal energy source, the star's helium core is unable to support itself against its own gravity and begins to shrink. The star at this stage is in the **hydrogen shell-burning** (p. 334) phase, with nonburning helium at the center surrounded by a layer of burning hydrogen. The energy released by the contracting helium core heats the hydrogen-burning shell, greatly increasing the nuclear reaction rates there. As a result, the star becomes much brighter, while the envelope expands and cools. A solar-mass star moves off the main sequence on the H–R diagram first along the **subgiant branch** (stage 8; p. 334), then almost vertically up the **red giant branch** (stage 9; p. 334).



LO2 As the helium core contracts, it heats up. Eventually, helium begins to fuse into carbon. In a star like the Sun, helium burning begins explosively, in the **helium flash** (p. 335). The flash expands the core and reduces the star's luminosity, sending it onto the **horizontal branch** (stage 10; p. 335) of the H–R diagram. The star now has a core of burning helium surrounded by a shell of burning hydrogen. An inner core of nonburning carbon forms, shrinks, and heats the overlying burning layers, and the star once again becomes a red giant, even more luminous than before (stage 11). The core of a solar-mass star never becomes hot enough to fuse carbon. Such a star continues to brighten and expand until its envelope is ejected into space, forming a **planetary nebula** (stage 12; p. 336). At that point the core becomes visible as a hot, faint, and extremely dense white dwarf (stage 13). The white dwarf cools and fades, eventually becoming a cold **black dwarf** (stage 14; p. 339).

LO3 Although most white dwarfs simply cool and dim with time, some may become explosively active in the form of a **nova** (p. 340). A nova is a star that suddenly increases greatly in brightness, then slowly fades back to its normal appearance over a period of months. It is the result of a white dwarf in a binary system drawing hydrogen-rich material from its companion. The gas spirals inward in an **accretion disk** (p. 341) and builds up on the white dwarf's surface, eventually becoming hot and dense enough for the hydrogen to burn explosively, temporarily causing a large increase in the dwarf's luminosity.

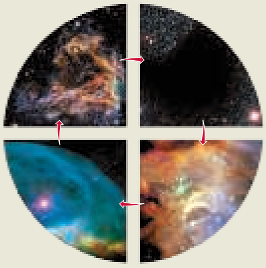
LO4 Stars more massive than about 8 solar masses form heavier and heavier elements in their cores, at a more and more rapid pace. As they evolve into **red supergiants** (p. 342), their cores form a layered structure consisting of burning shells of successively heavier elements. The process stops at iron, whose nuclei can neither be fused together nor split to produce energy. As a star's iron core grows in mass, it

eventually becomes unable to support itself against gravity and begins to collapse. At the high temperatures produced during the collapse, iron nuclei are broken down into protons and neutrons. The protons combine with electrons to form more neutrons. Eventually, when the core becomes so dense that the neutrons are effectively brought into physical contact with one another, their resistance to further squeezing stops the collapse and the core rebounds, sending a violent shock wave out through the rest of the star. The star explodes in a **core-collapse supernova** (p. 344).

LO5 **Type I supernovae** (p. 345) are hydrogen poor and have light curves similar in shape to those of novae. **Type II supernovae** (p. 345) are hydrogen rich and have a characteristic bump in the light curve a few months after maximum. A Type II supernova is a core-collapse supernova. A Type I supernova is a **carbon-detonation supernova** (p. 346), which occurs when a white dwarf in a binary system collapses and then explodes as its carbon ignites. We can see evidence for a past supernova in the form of a **supernova remnant** (p. 347), a shell of exploded debris surrounding the site of the explosion and expanding into space at a speed of thousands of kilometers per second.

LO6 The theory of stellar evolution can be tested by observing star clusters. At any instant, stars with masses above the cluster's **main-sequence turnoff** (p. 351) have evolved off the main sequence. By comparing a cluster's main-sequence turnoff mass with theoretical predictions, astronomers can determine the cluster's age. Many globular clusters show evidence of multiple stellar populations, whose origin is not yet understood.

LO7 All elements heavier than helium formed in evolved stars or in supernova explosions. With each new generation of stars, the fraction of heavy elements in the universe increases. Comparisons between theoretical predictions of element production and observations of element abundances in the Galaxy provide strong support for the theory of stellar evolution.



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Problems labeled POS explore the process of science. VIS problems focus on reading and interpreting visual information. LO connects to the introduction's numbered Learning Outcomes.

REVIEW AND DISCUSSION

1. How long can a star like the Sun keep burning hydrogen in its core?
2. LO1 Why is the depletion of hydrogen in the core of a star such an important event?
3. What makes an ordinary star become a red giant?
4. Roughly how big (in AU) will the Sun become when it enters the red giant phase?
5. LO2 How long does it take for a star like the Sun to evolve from the main sequence to the top of the red giant branch?
6. What is the helium flash?
7. How do stars of low mass die? How do stars of high mass die?
8. What is a planetary nebula? With what stage of stellar evolution is it associated?
9. What are white dwarfs? What is their ultimate fate?
10. LO3 Under what circumstances will a binary star produce a nova?
11. LO4 What occurs in a massive star to cause it to explode?
12. What are the observational differences between Type I and Type II supernovae?
13. LO5 How do the mechanisms that cause Type I and Type II supernovae explain their observed differences?
14. LO6 POS What evidence do we have that many supernovae have occurred in our Galaxy?
15. LO7 POS What do stars in clusters tell us about the various stages of stellar evolution?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. All of the single red-dwarf stars that ever formed are still on the main sequence today. (T/F)
2. The Sun will get brighter as it begins to run out of fuel in its core. (T/F)
3. A planetary nebula is the disk of matter around a star that will eventually form a planetary system. (T/F)
4. Nuclear fusion in the core of a massive star cannot create elements much heavier than iron. (T/F)
5. A nova is a sudden outburst of light coming from an old main-sequence star. (T/F)
6. It takes less and less time to fuse heavier and heavier elements inside a high-mass star. (T/F)
7. In a core-collapse supernova, the outer part of the core rebounds from the inner, high-density core, destroying the entire outer part of the star. (T/F)
8. Because of stellar nucleosynthesis, the spectra of old stars show more heavy elements than those of young stars. (T/F)
9. A white dwarf is supported by the pressure of tightly packed (a) electrons; (b) protons; (c) neutrons; (d) photons.
10. A star like the Sun will end up as a (a) blue giant; (b) white dwarf; (c) binary star; (d) red dwarf.
11. A white dwarf can dramatically increase in brightness only if it (a) has another star nearby; (b) can avoid nuclear fusion in its core; (c) is spinning very rapidly; (d) is descended from a very massive star.
12. Nuclear fusion in the Sun will (a) never create elements heavier than helium; (b) create elements up to and including oxygen; (c) create all elements up to and including iron; (d) create some elements heavier than iron.
13. Most of the carbon in our bodies originated in (a) the core of the Sun; (b) the core of a red giant star; (c) a supernova; (d) a nearby galaxy.
14. **VIS** If the evolutionary track in *Overlay 3*, showing a Sun-like star, were instead illustrating a significantly more massive star, its starting point (stage 7) would be (a) up and to the right; (b) down and to the left; (c) up and to the left; (d) down and to the right.
15. **VIS** Figure 12.20 (Supernova Light Curves) indicates that a supernova whose luminosity declines steadily in time is most likely associated with a star that is (a) without a binary companion; (b) more than eight times the mass of the Sun; (c) on the main sequence; (d) comparable in mass to the Sun.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ Calculate the average density of a red giant core of mass 0.25 solar masses and radius 15,000 km. Compare this with the average density of the giant's envelope, if the mass of the envelope is 0.5 solar masses and its radius is 0.5 AU. Compare each with the central density of the Sun. ∞ ***(Sec. 9.2)***
2. ■■■ A main sequence star at a distance of 20 pc is barely visible through a certain telescope. The star subsequently ascends the giant branch, during which time its temperature drops by a factor of three and its radius increases 100-fold. What is the new maximum distance at which the star would still be visible using the same telescope?
3. ■■ The Sun will reside on the main sequence for years. If the luminosity of a main-sequence star is proportional to the fourth power of the star's mass, what is the mass of a star that is just now leaving the main sequence in a cluster that formed (a) 400 million years ago? (b) 2 billion years ago?
4. ■ How long will it take the Sun's planetary nebula, expanding at a speed of 20 km/s, to reach the orbit of Neptune? How long to reach the nearest star?
5. ■ What are the escape speed (in km/s) and surface gravity (relative to Earth's gravity) of Sirius B (Table 12.2)? ∞ ***(More Precisely 5-1)***
6. ■■■ A certain telescope could just detect the Sun at a distance of 10,000 pc. What is the apparent magnitude of the Sun at this distance? (For convenience, take the Sun's absolute magnitude to be 5.) What is the maximum distance at which the telescope could detect a nova having a peak luminosity of 10^5 solar luminosities? Repeat the calculation for a supernova having a peak luminosity 10^{10} times that of the Sun.
7. ■■ At what distance would the supernova in the previous question look as bright as the Sun (apparent magnitude -27)? Would you expect a supernova to occur that close to us?
8. ■■ A (hypothetical) supernova at a distance of 150 pc has an absolute magnitude of -20. Compare its apparent magnitude with that of (a) the full Moon; (b) Venus at its brightest (see Figure 10.6). Would you expect a supernova to occur so close to us?
9. ■ The Crab Nebula is now about 1 pc in radius. If it was observed to explode in A.D. 1054, roughly how fast is it expanding? (Assume constant expansion velocity. Is that a reasonable assumption?)
10. ■■ A supernova's energy is often compared to the total energy output of the Sun over its lifetime. Using the Sun's current luminosity, calculate the total solar energy output, assuming a 10^{10} year main-sequence lifetime. Using Einstein's formula $E = mc^2$ calculate the equivalent amount of mass, in Earth masses. ∞ ***(Sec. 9.5)***

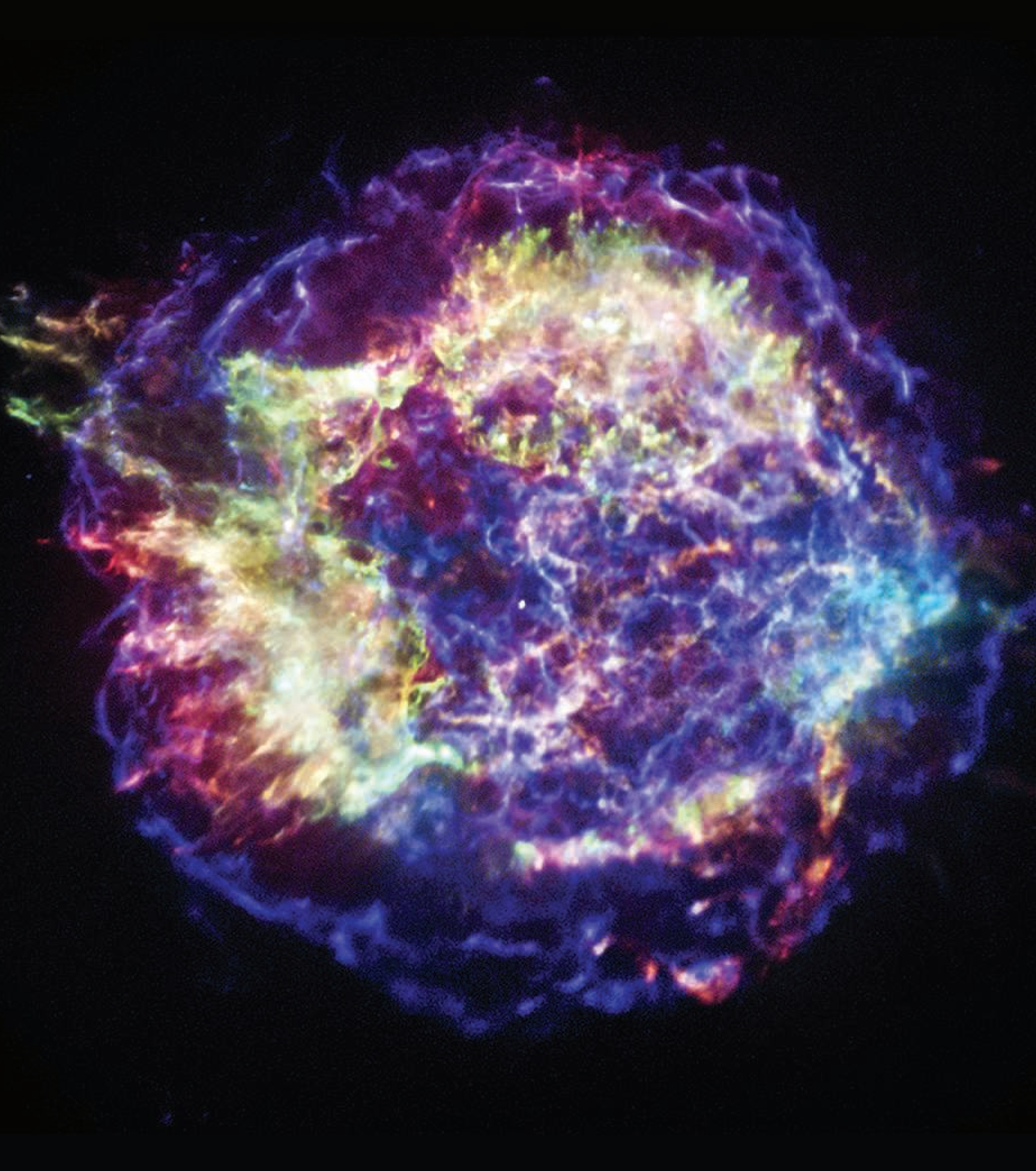
ACTIVITIES

Collaborative

1. Open clusters are generally found in the plane of the Galaxy. If you can see the hazy band of the Milky Way arcing across your night sky—in other words, if you are far from city lights and looking at an appropriate time of night and year—you can simply sweep with your binoculars along the Milky Way. Numerous "clumps" of stars will pop into view. Many will turn out to be open star clusters. The most easily visible clusters are those in the Messier catalog, but there are many others besides those. How many clusters can you find that are *not* on Messier's list?
2. Globular star clusters are harder to find. They are intrinsically larger, but they are also much farther away and therefore appear smaller in the sky. The most famous globular cluster visible from the Northern Hemisphere is M13 in the constellation Hercules, visible on spring and summer evenings. It contains half million or so of the Galaxy's most ancient stars. It may be glimpsed through binoculars as a little ball of light, located about one-third of the way from the star Eta to the star Zeta in the Keystone asterism of the constellation Hercules. Telescopes reveal this cluster as a magnificent, symmetrical grouping of stars. Can you find the following well-known globular clusters: M3, M4, M5, M13, M15? Look online or in a star chart for details on how to locate them.

Individual

1. Can you find the Hyades cluster? It lies about 46 pc away in the constellation Taurus, making up the "face" of the bull. It appears to surround the very bright star Aldebaran, the bull's eye, which makes it easy to locate in the sky. Aldebaran is a low-mass red giant, about twice the mass of the Sun, probably on the asymptotic giant branch of its evolution. Despite appearances, it is not part of the Hyades cluster. In fact, it lies only about half as far away—about 20 pc from Earth
2. In 1758, Charles Messier discovered the sky's most legendary supernova remnant, now called M1, or the Crab Nebula. It is located northwest of Zeta Tauri, the star that marks the southern tip of the horns of Taurus the Bull. Try to find it. An 8-inch telescope reveals the Crab's oval shape, but it will appear faint; a 10-inch or larger telescope reveals some of its famous filamentary structure.
3. The Ring Nebula (M57) is perhaps the most famous planetary nebula. At magnitude 9, it is faint, but a 6-inch or larger telescope should show its structure. To locate it, find Beta and Gamma Lyrae, the second and third brightest stars in the constellation Lyra. The ring lies between them, about one-third the way from Beta to Gamma. Don't expect the Ring to look as colorful as the *Hubble* images you may have seen! Can you see any color in the ring?



13

Neutron Stars and Black Holes

Strange States of Matter

Our study of stellar evolution has led us to some very unusual and unexpected objects. Red giants, white dwarfs, and supernova explosions surely represent extreme states of matter completely unfamiliar to us here on Earth. Yet, stellar evolution can have even more bizarre consequences. The strangest states of all result from the catastrophic implosion–explosion of stars much more massive than our Sun.

Neutron stars and black holes are among the most exotic objects in the universe. They are the end of the road for massive stars, and their bizarre properties boggle the imagination. Yet theory and observation seem to agree that, fantastic or not, they really do exist in space.

THE BIG PICTURE

The almost unimaginable violence of supernova explosions may create objects so extreme in their behavior that they require us to reconsider some of our most cherished laws of physics. They open up a science fiction writer's dream of fantastic phenomena that border on reality. They may even one day force scientists to construct a whole new theory of the universe.

Neutron stars and black holes are among the most exotic members of the vast population of stars throughout the universe. These objects represent the end states of stellar systems, yet despite their bizarre nature, they do seem to agree quite well with models of stellar evolution. This stunning image combines X-ray observations from the *Chandra* satellite, with red, green, and blue representing low, medium, and high X-ray energies. This debris field spread across 10 light-years is known as Cassiopeia A, the remnant of a supernova whose radiation first reached Earth about 300 years ago. The white dot at the center may be a neutron star created at the precise center of the blast. *(CXC)*

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** List the key properties of neutron stars, and outline how these strange objects are formed.
- **LO2** Describe the nature and origin of pulsars, and explain how pulsars provide evidence for the existence of neutron stars.
- **LO3** List and explain some of the observable properties of neutron star binary systems.
- **LO4** Outline the basic characteristics of gamma-ray bursts and the leading theoretical attempts to explain them.
- **LO5** Describe Einstein's theories of relativity, and explain how they relate to neutron stars and black holes.
- **LO6** Explain how black holes are formed, and describe their effects on matter and radiation in their vicinity.
- **LO7** Relate the phenomena that occur near black holes to the warping of space around them.
- **LO8** Describe the difficulties in observing black holes, and list some ways in which black holes can be detected.

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13.1 Neutron Stars

What remains after a supernova explosion? Is the original star blown to bits and dispersed into interstellar space, or does some portion of it survive? For a Type I (carbon-detonation) supernova, most astronomers regard it as unlikely that anything is left behind after the explosion. ∞ *(Sec. 12.5)* The entire star is shattered by the blast. However, for a Type II (core-collapse) supernova, theoretical calculations indicate that part of the star should survive the explosion.

Recall that in a Type II supernova, the iron core of a massive star collapses until its neutrons effectively come into contact with one another. At that point the central portion of the core rebounds, creating a powerful shock wave that races outward through the star, violently expelling matter into space. ∞ *(Sec. 12.4)* The key point here is that the shock wave does not start at the very center of the collapsing core. The innermost part of the core—the region that rebounds—remains intact as the shock wave it produces destroys the rest of the star. After the violence of the supernova has subsided, this ultracompressed ball of neutrons is all that is left. Researchers call this core remnant a **neutron star.**

Neutron stars are extremely small and very massive. Composed purely of neutrons packed together in a tight ball about 20 km across, a typical neutron star is not much bigger than a small asteroid or a terrestrial city (Figure 13.1), yet its mass is greater than that of the Sun. With so much mass squeezed into such a small volume, neutron stars are incredibly dense—some 10^{17} or even 10^{18} kg/m^3, nearly a billion times denser than a white dwarf. ∞ *(Sec. 12.3)* A thimbleful of neutron star material would weigh 100 million tons—about as much as a terrestrial mountain.

CONCEPT CHECK

Are all supernovae expected to lead to neutron stars?

Neutron stars are solid objects. Provided that a sufficiently cool one could be found, you might even imagine standing on it. However, this would not be easy, as its gravity is immensely strong. A 70-kg human would weigh the Earth equivalent of about 1 billion kilograms (1 million tons). The severe pull of a neutron star's gravity would flatten you much thinner a piece of paper.

In addition to large mass and small size, newly formed neutron stars have two other very important properties. First, they *rotate* extremely rapidly, with periods measured in fractions of a second. This is a direct result of the law of conservation of angular momentum (Chapter 4), which tells us that any rotating body must spin faster as it shrinks, and the core of the parent star almost certainly had some rotation before it began to collapse. ∞ *(More Precisely 4-2)* Second, they have very strong *magnetic fields*. The original field of the parent star is amplified as the collapsing core squeezes the magnetic field lines closer together, creating a magnetic field trillions of times stronger than Earth's.

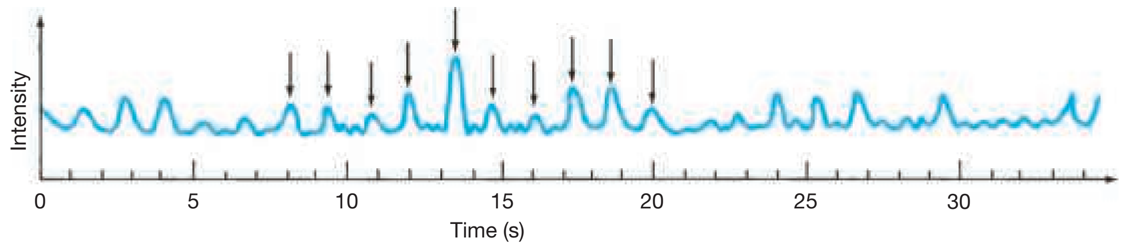
In time, theory indicates, a neutron star will spin more and more slowly as it radiates its energy into space, and its magnetic field will diminish. However, for a few million years after its birth, these two properties combine to provide the primary means by which this strange object can be detected and studied, as we now discuss.

▲ **FIGURE 13.1 Neutron Star** Neutron stars are not much larger than many of Earth's major cities. In this fanciful comparison, a typical neutron star sits alongside Manhattan Island. *(NASA)*

13.2 Pulsars

The first observation of a neutron star occurred in 1967 when Jocelyn Bell, a graduate student at Cambridge University, observed an astronomical object emitting radio radiation in the form of rapid *pulses* (Figure 13.2). Each pulse consisted of a roughly 0.01-s burst of radiation, separated by precisely 1.34 s from the next.

More than 1500 of these pulsating objects are now known. They are called **pulsars.** Each has its own characteristic pulse shape and period. Observed pulsar periods are generally quite short, ranging from about a few milliseconds to about a second, corresponding to flashing rates of between one and several



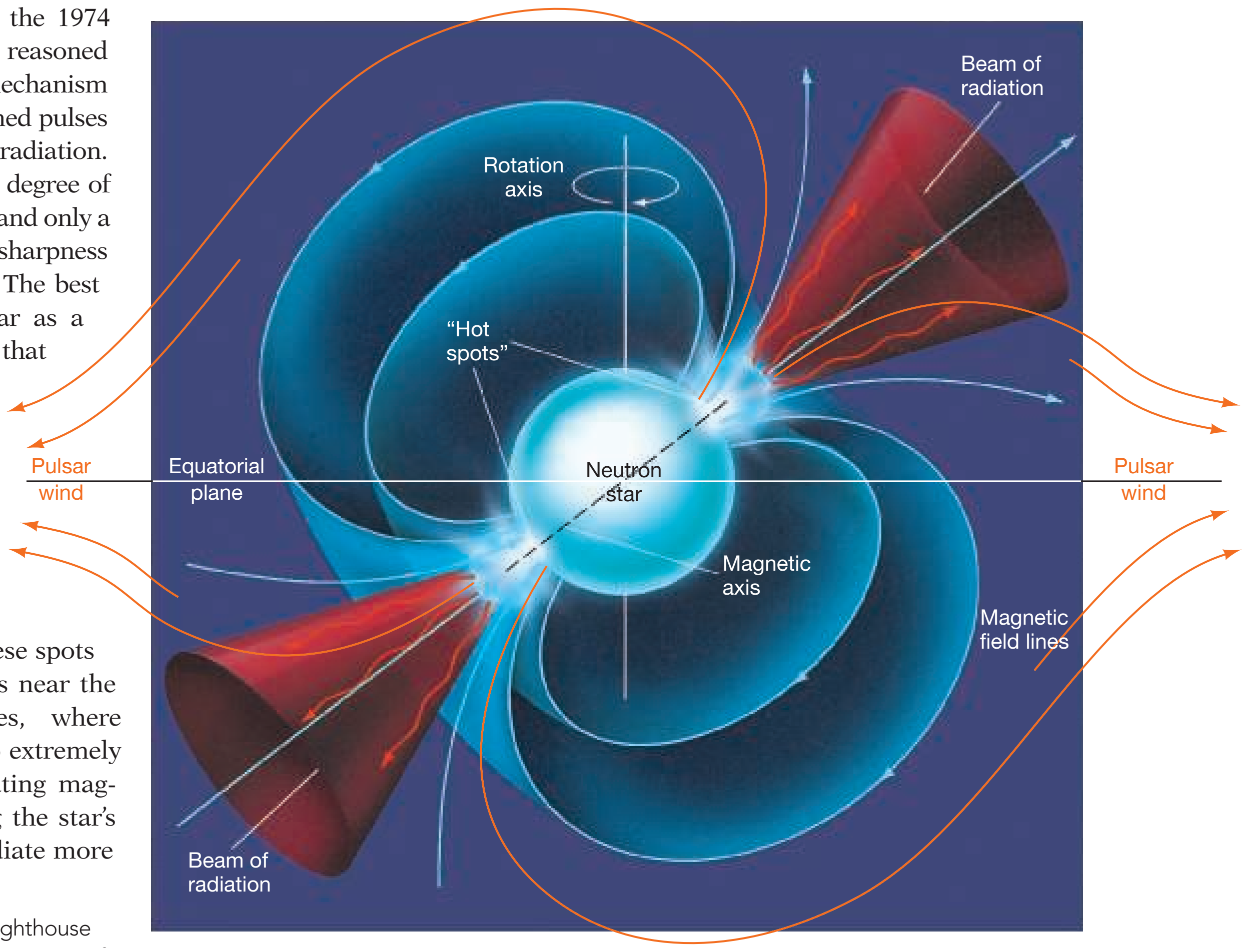
◀ **FIGURE 13.2 Pulsar Radiation** This recording shows the regular change in the intensity of the radio radiation emitted by the first pulsar discovered, known as CP1919. Some of the object's pulses are marked.

hundred times per second. In some cases, the periods are extremely stable—in fact, constant to within a few seconds in a million years—making pulsars the most accurate natural clocks known in the universe, more accurate even than the best atomic clocks on Earth.

A Pulsar Model

When Bell made her discovery in 1967, she did not know what she was looking at. Indeed, no one at the time knew what a pulsar was. The explanation won Bell's thesis advisor, Anthony Hewish, the 1974 Nobel Prize in physics. Hewish reasoned that the only physical mechanism consistent with such precisely timed pulses is a small, rotating source of radiation. Only rotation can cause the high degree of regularity of the observed pulses, and only a small object can account for the sharpness of each pulse (see Section 13.4). The best current model describes a pulsar as a compact, spinning neutron star that periodically flashes radiation toward Earth.

Figure 13.3 outlines the main features of this pulsar model. Two "hot spots," either on the surface of a neutron star or in the magnetosphere just above it, continuously emit radiation in a narrow beam. These spots are most likely localized regions near the neutron star's magnetic poles, where charged particles, accelerated to extremely high energies by the star's rotating magnetic field, emit radiation along the star's magnetic axis. The hot spots radiate more



▶ **FIGURE 13.3 Pulsar Model** The "lighthouse model" of neutron star emission explains many of the observed properties of pulsars. Charged particles, accelerated by the magnetism of the neutron star, flow along the magnetic field lines, producing radio radiation that beams outward. At greater distances from the star, the field lines channel these particles into a high-speed outflow in the star's equatorial plane, forming a pulsar wind. The beam sweeps across the sky as the neutron star rotates. If it happens to intersect Earth, we see a pulsar.

A lighthouse beacon is a good analogy for a rotating pulsar.

ANIMATION/VIDEO
Pulsar in Crab Nebula

CONCEPT CHECK

Why don't we see pulsars at the centers of all supernova remnants?

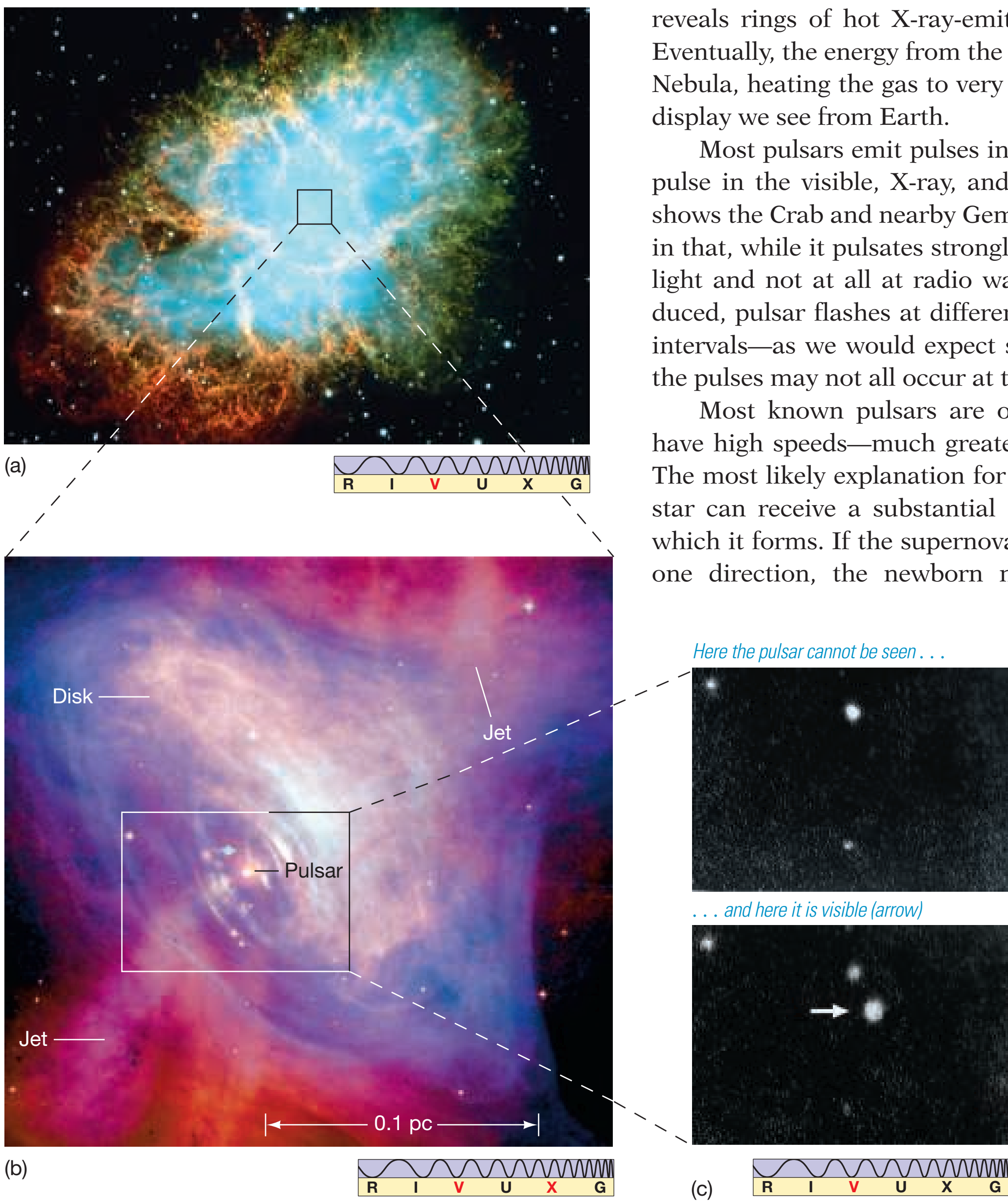
or less steadily, and the resulting beams sweep through space like a revolving lighthouse beacon as the neutron star rotates. Indeed, this pulsar model is often known as the **lighthouse model.** If the neutron star happens to be oriented such that one of the rotating beams sweeps across Earth, then we see the pulses. The period of the pulses is the star's rotation period.

A few pulsars are definitely associated with supernova remnants, clearly establishing those pulsars' explosive origin, although not all such remnants have a detectable pulsar within them. Figure 13.4(c) shows optical images of the Crab pulsar at the center of the Crab supernova remnant (Figure 13.4a). *(Sec. 12.5)* By observing the speed and direction of the Crab's ejected matter, astronomers can work backward to pinpoint the location in space at which the explosion must have occurred. It corresponds to the location of the pulsar. This is all that remains of the once massive star whose supernova was observed in 1054.

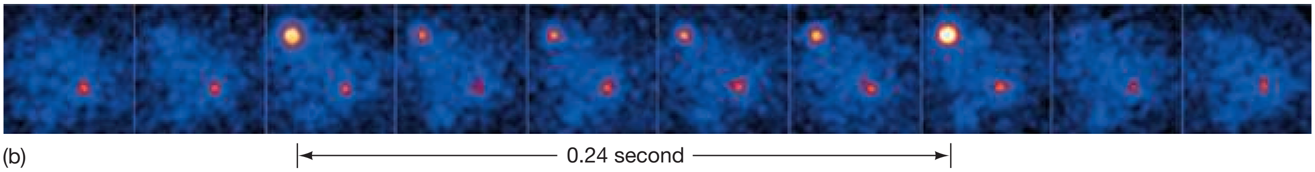
As indicated in Figure 13.3, the neutron star's strong magnetic field and rapid rotation channel high-energy particles from near the star's surface into the surrounding nebula. The result is an energetic *pulsar wind* that flows outward at almost the speed of light, primarily in the star's equatorial plane. Figure 13.4(b) shows this process in action in the Crab—this combined *Hubble/Chandra* image reveals rings of hot X-ray-emitting gas moving rapidly away from the pulsar. Eventually, the energy from the pulsar wind is deposited in the surrounding Crab Nebula, heating the gas to very high temperatures and powering the spectacular display we see from Earth.

Most pulsars emit pulses in the form of radio radiation. However, some also pulse in the visible, X-ray, and gamma-ray parts of the spectrum. Figure 13.5 shows the Crab and nearby Geminga pulsars in gamma rays. Geminga is unusual in that, while it pulsates strongly in gamma rays, it is barely detectable in visible light and not at all at radio wavelengths. Whatever types of radiation are produced, pulsar flashes at different frequencies all occur at regular, repeated time intervals—as we would expect since they arise from the same object—although the pulses may not all occur at the same instant.

Most known pulsars are observed (usually by Doppler measurements) to have high speeds—much greater than the typical speeds of stars in the Galaxy. The most likely explanation for these anomalously high speeds is that a neutron star can receive a substantial "kick" due to asymmetries in the supernova in which it forms. If the supernova's enormous energy is channeled even slightly in one direction, the newborn neutron star/pulsar can recoil in the opposite



◄ **FIGURE 13.4 Crab Pulsar** In the core of the Crab Nebula (a), the Crab pulsar (c) blinks on and off about 30 times each second. In the top frame, the pulsar is off; in the bottom frame, it is on (arrow). (b) This *Chandra* X-ray image of the Crab, superimposed on a *Hubble* optical image, shows the central pulsar, as well as rings of hot X-ray-emitting gas in the equatorial plane, driven outward by the pulsar wind. Also visible in the image is a jet of hot gas escaping perpendicular to the equatorial plane. *(ESO; NASA; UC/Lick Observatory)*



(b)

direction with a speed of many tens or even hundreds of kilometers per second. Thus, observations of pulsar velocities give theorists additional insight into the detailed physics of supernovae.

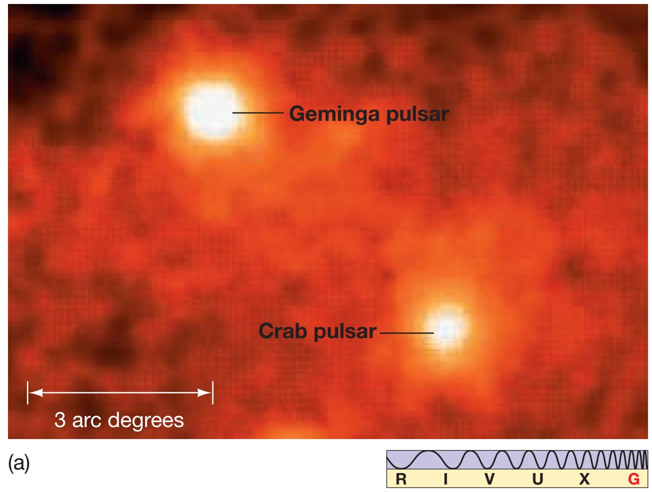
Neutron Stars and Pulsars

All pulsars are neutron stars, but not all neutron stars are pulsars, for two reasons. First, the two ingredients that make the neutron star pulse—rapid rotation and strong magnetic field—both diminish with time, so the pulses gradually weaken and become less frequent. Theory indicates that within a few tens of millions of years, the pulses have all but stopped. Second, even a young, bright pulsar is not necessarily visible from Earth. The pulsar beam depicted in Figure 13.3 is relatively narrow—perhaps as little as a few degrees across. Only if the neutron star happens to be oriented in just the right way do we see pulses. When we see the pulses from Earth, we call the object a pulsar. Note that we are using the term "pulsar" here to mean the pulsing object we observe if the beam crosses Earth. However, many astronomers use the word more generically to mean *any* young neutron star producing beams of radiation as in Figure 13.3. Such an object will be a pulsar as seen from some directions—just not necessarily ours!

Figure 13.6 shows *Hubble* images of a neutron star that is not a pulsar. First identified by X-ray observations, this object is just 30 km across and has a surface temperature of about 700,000 K. Despite this enormous temperature, its small size means that it is very faint—just 25th magnitude in visible light. ∞ *(Sec. 10.4)* The star is thought to be about 1 million years old, lies about 60 pc away, and is moving at a speed of 110 km/s across our line of sight. Such faint objects are very difficult to detect, however, and a detection of a "bare" neutron star like this is a rare event. Most cataloged neutron stars have been detected either as pulsars or by their interaction with a "normal" stellar companion in a binary system (see Section 13.3).

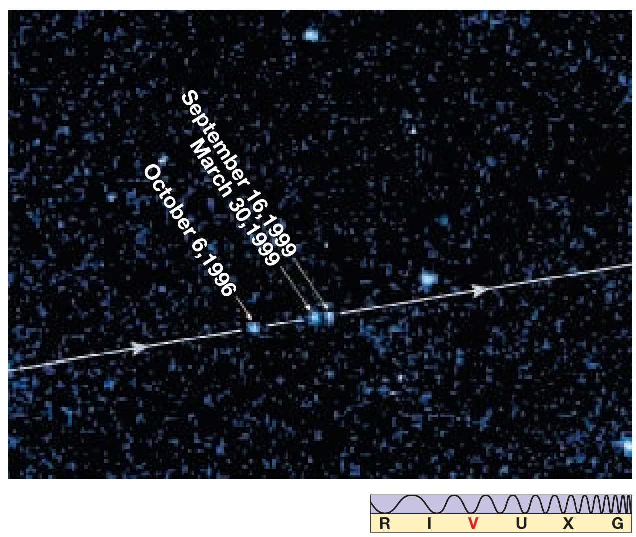
Given our current knowledge of star formation, stellar evolution, and neutron stars, observations of pulsars are consistent with the ideas that (1) *every* high-mass star dies in a supernova explosion, (2) most supernovae leave a neutron star behind (a few result in black holes, as discussed in a moment), and (3) *all* young neutron stars emit beams of radiation, just like the pulsars we actually detect. On the basis of estimates of the rate at which massive stars have formed over the lifetime of the Milky Way, astronomers reason that, for every pulsar we know of, there must be several hundred thousand more neutron stars moving unseen somewhere in the Galaxy. Some formed relatively recently—less than a few million years ago—and simply happen not to be beaming their energy toward Earth. However, the vast majority are old, their youthful pulsar phase long past.

Neutron stars (and black holes too) were suggested by theory long before they were actually observed, although their extreme properties made many scientists doubt that they would ever be found in nature. The fact that we now have strong observational evidence, not just for their existence, but also for the vitally important roles they play in many areas of high-energy astrophysics, is yet another testament to the fundamental soundness of the theory of stellar evolution.



(a)

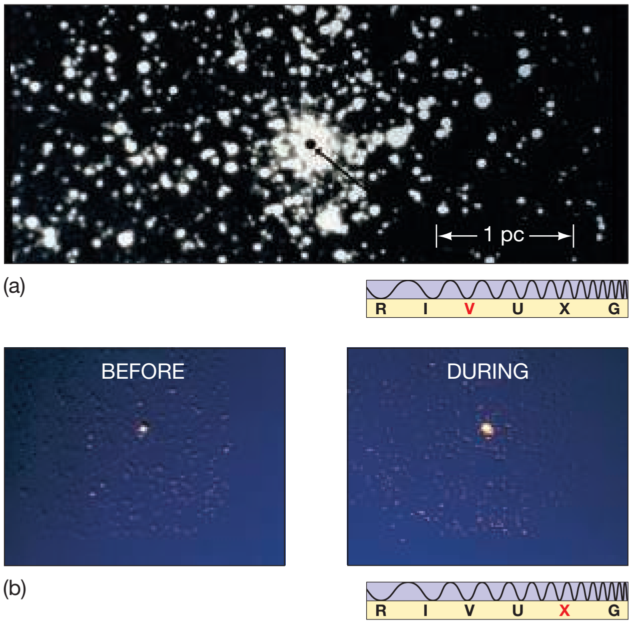
▲ **FIGURE 13.5 Gamma-Ray Pulsars** (a) The Crab and Geminga pulsars lie fairly close to one another in the sky. Unlike the Crab, Geminga is barely visible at optical wavelengths, and undetectable in the radio region of the spectrum. (b) Sequence of *Compton Gamma-Ray Observatory* images showing Geminga's 0.24-s pulse period. *(NASA)*



▲ **FIGURE 13.6 Isolated Neutron Star** This lone neutron star was first detected by its X-ray emission and subsequently imaged by *Hubble*. This 700,000-K object lies about 60 pc from Earth and is thought to be about 1 million years old. This triple exposure shows the star streaking across the sky at more than 100 km/s. *(NASA)*

13.3 Neutron Star Binaries

We noted in Chapter 10 that most stars are members of binary systems. *(Sec. 10.7)* Although many pulsars are known to be isolated (that is, not part of any binary), at least some do have binary companions, and the same is true of neutron stars in general (that is, even the ones not seen as pulsars). One important consequence of this is that some neutron star masses have been determined very accurately. Most of the measured masses are fairly close to 1.4 times the mass of the Sun—the Chandrasekhar mass of the stellar core that collapsed to form the neutron star remnant—although a neutron star with a mass twice that of the Sun has recently been reported.



▲ FIGURE 13.7 **X-Ray Burster** An X-ray burster produces a sudden, intense flash of X-rays, followed by a period of relative inactivity lasting as long as several hours. Then another burst occurs. (a) An optical photograph of the globular star cluster Terzan 2, showing a 2" dot at the center where the X-ray bursts originate. (b) X-ray images taken before and during the outburst. The most intense X-rays correspond to the position of the black dot shown in (a). *(SAO)*

X-Ray Sources

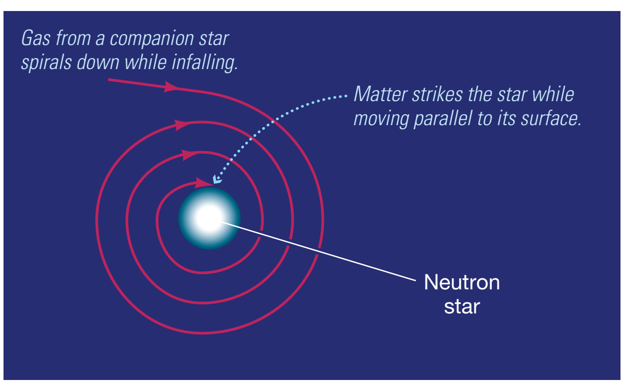
With the launch of the first orbiting X-ray telescopes in the 1970s, numerous X-ray sources were found near the central regions of our Galaxy and also near the centers of a few globular star clusters. *(Sec. 11.6)* Some of these sources, known as **X-ray bursters,** emit much of their energy in violent eruptions, each thousands of times more luminous than our Sun but lasting only seconds. A typical burst is shown in Figure 13.7.

The X-ray emission is thought to arise on or near neutron stars that are members of binary systems. Matter torn from the surface of the companion by the neutron star's strong gravitational pull accumulates on the neutron star's surface. (Figure 12.14 shows the white dwarf equivalent.) *(Sec. 12.3)* The gas forms an accretion disk around the neutron star, then slowly spirals inward. The inner portions of the disk become extremely hot, releasing a steady stream of X-rays.

As gas builds up on the neutron star's surface, its temperature rises due to the pressure of overlying material. Eventually, it becomes hot enough to fuse hydrogen. The result is a sudden period of rapid nuclear burning that releases a huge amount of energy in a brief but intense X-ray burst. After several hours of renewed accumulation, a fresh layer of matter produces the next burst. The mechanism is similar to that responsible for a nova explosion on a white dwarf, except that it occurs on a far more violent scale because of the neutron star's much stronger surface gravity.

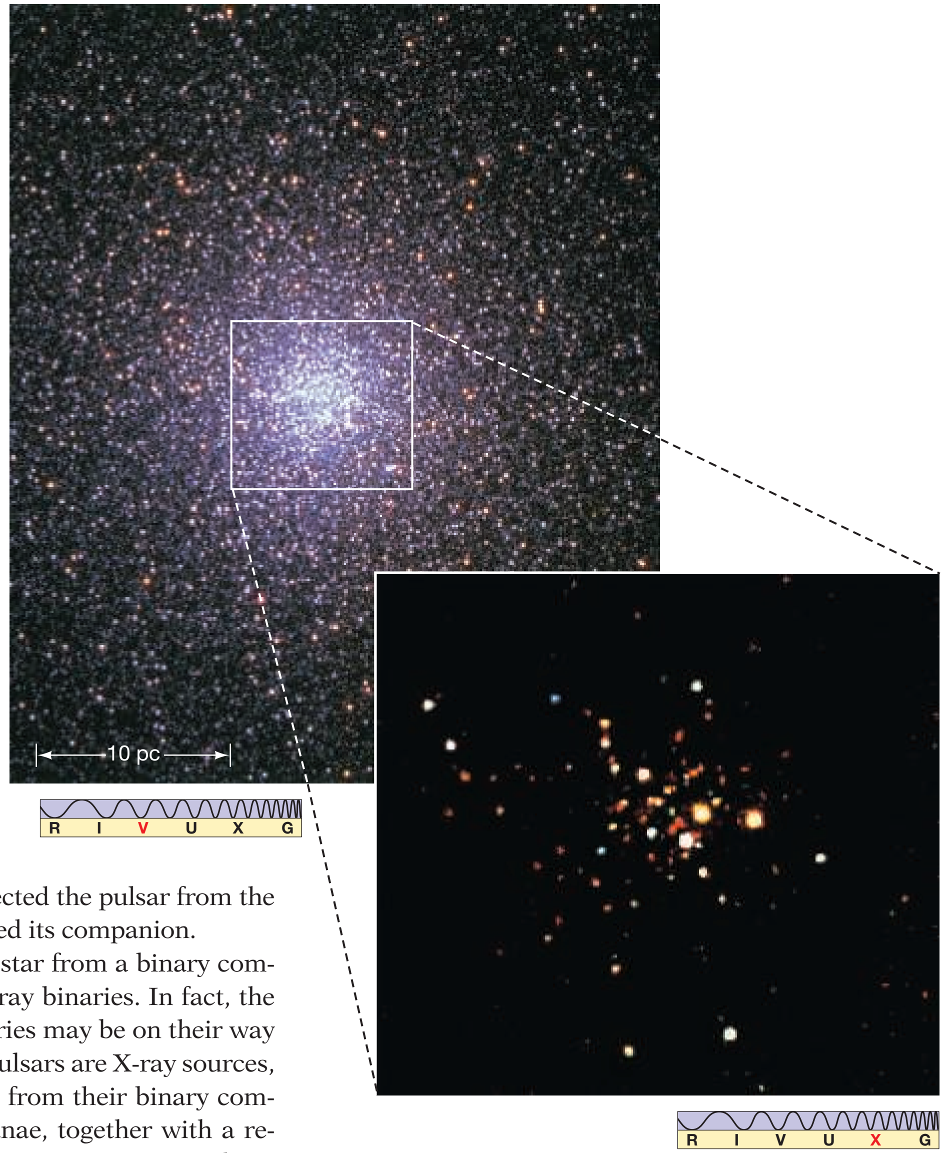
Millisecond Pulsars

In the mid-1980s astronomers discovered an important new category of pulsars—a class of very rapidly rotating objects called **millisecond pulsars.** These objects spin hundreds of times per second (that is, their pulse periods are a few milliseconds, 0.001 s). This speed is about as fast as a typical neutron star can spin without flying apart. In some cases the star's equator is moving at more than 20 percent of the speed of light. This suggests a phenomenon bordering on the incredible—a cosmic object just 20 km across, more massive than our Sun, spinning almost at breakup speed, making nearly 1000 complete revolutions *every second*. Yet the observations and their interpretation leave little room for doubt. More than 200 millisecond pulsars are now known.



▲ FIGURE 13.8 **Millisecond Pulsar** As infalling matter strikes the star, it moves almost parallel to the surface, so it tends to make the star spin faster. Eventually, this process can result in a millisecond pulsar—a neutron star spinning at the incredible rate of hundreds of revolutions per second.

The story of these remarkable objects is further complicated by the fact that many of them—about two-thirds—are found in globular clusters. This is odd because globular clusters are at least 10 billion years old, yet Type II supernovae (the kind that create neutron stars) are associated with massive stars that explode within a few tens of *millions* of years after their formation, and no stars have formed in any globular cluster since the cluster came into being. *(Secs. 11.6, 12.4)* Thus, no new neutron star has been produced in a globular cluster in a very long time. Furthermore, as mentioned earlier, the pulsar produced in a supernova explosion is



▶ **FIGURE 13.9 Cluster X-Ray Binaries** The dense core of the old globular cluster 47 Tucanae harbors more than 100 separate X-ray sources (shown in the *Chandra* image at bottom right). More than half of these are thought to be binary millisecond pulsars, still accreting small amounts of gas from their companions after an earlier period of mass transfer spun them up to millisecond speeds. *(ESO; NASA)*

expected to slow down and fade away in only a few tens of millions of years—after 10 billion years, its rotation rate should be very slow. The rapid rotation of the pulsars found in globular clusters therefore cannot be a relic of their birth. These pulsars must have been "spun up"—that is, had their rotation rates increased—by some other, much more recent, mechanism.

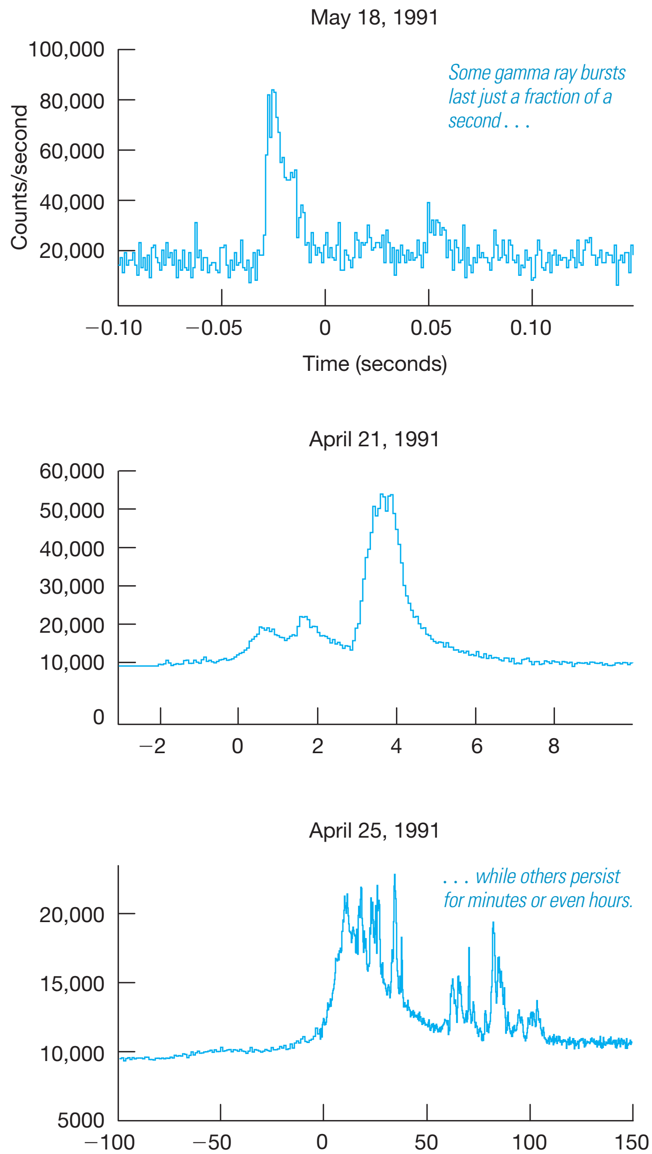
The most likely explanation for the high rotation rate of millisecond pulsars is that they have been spun up by drawing in matter from a companion star. As matter spirals down onto the neutron star's surface in an accretion disk, it provides the "push" needed to make the neutron star spin faster (Figure 13.8). Theoretical calculations indicate that this process can spin the star up to breakup speed in about 100 million years. This picture is supported by the finding that, of the 140 or so millisecond pulsars observed in globular clusters, roughly half are known currently to be members of binary systems. The remaining solo millisecond pulsars were probably formed when an encounter with another star ejected the pulsar from the binary or when the pulsar's own intense radiation destroyed its companion.

Notice that the scenario of accretion onto a neutron star from a binary companion is the same as the one we just used to explain X-ray binaries. In fact, the two phenomena are very closely linked. Many X-ray binaries may be on their way to becoming millisecond pulsars, and many millisecond pulsars are X-ray sources, powered by the trickle of material still falling onto them from their binary companions. Figure 13.9 shows the globular cluster 47 Tucanae, together with a remarkable *Chandra* image of its core showing more than 100 X-ray sources—about 10 times the number that had been known in the cluster prior to *Chandra's* launch. Roughly half of these sources are millisecond pulsars; the cluster also contains two or three "conventional" neutron star binaries. Most of the remaining sources are white dwarf binaries, similar to those discussed in Chapter 12. ∞ *(Sec. 12.3)*

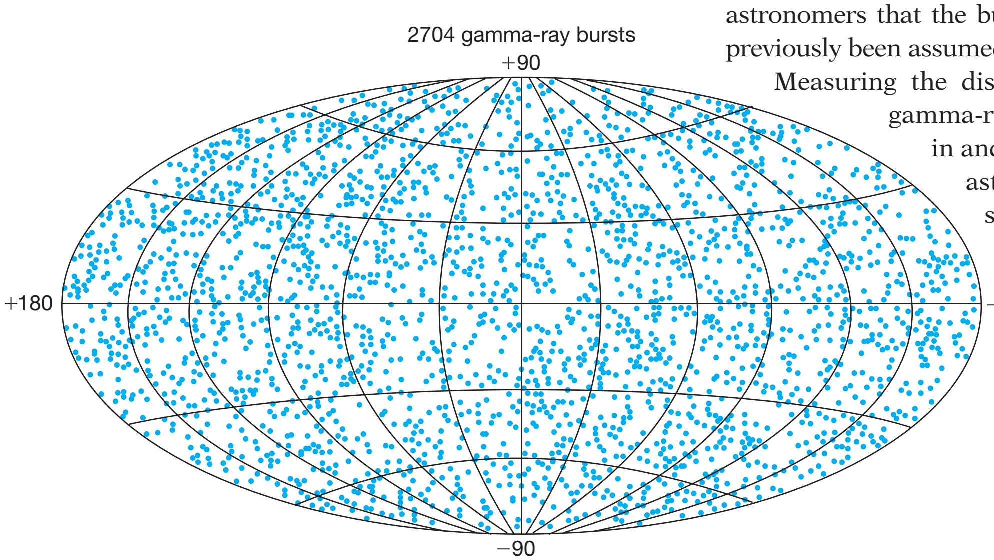
Pulsar Planets

Radio astronomers can capitalize on the precision with which pulsar signals repeat themselves to make extremely accurate measurements of pulsar motion. In 1992 radio astronomers at the Arecibo Observatory found that the pulse period of a millisecond pulsar lying some 500 pc from Earth exhibits tiny but regular fluctuations (at the level of about 1 part in 10^7) on two distinct time scales—67 and 98 days.

These fluctuations are caused by the Doppler effect as the pulsar wobbles back and forth in space under the combined gravitational pulls of two small bodies, each about three times the mass of Earth ∞ *(Sec. 4.4)*. One orbits the pulsar at a distance of 0.4 AU, the other at a distance of 0.5 AU, with orbital periods of 67 and 98 days, respectively. Further observations not only confirmed these findings, but also revealed the presence of a third body, with a mass comparable to that of Earth's Moon, orbiting just 0.2 AU from the pulsar.



(a)



(b)

These remarkable findings were the first definite evidence of planet-sized bodies outside our solar system. A few other millisecond pulsars have since been found also to have planets. However, it is unlikely that any of these planets formed in the same way as our own. Any planetary system orbiting the pulsar's parent star was almost certainly destroyed in the supernova explosion that created the pulsar. Scientists are uncertain about how these planets came into being. One possibility involves the binary companion that provided the matter necessary to spin the pulsar up to millisecond speeds. Possibly, the pulsar's intense radiation and strong gravity destroyed the companion, then spread its matter out into a disk (a little like the solar nebula) in whose cool outer regions the planets might have condensed.

Astronomers searched for decades for planets orbiting main-sequence stars like our Sun on the assumption that planets are a natural by-product of star formation. ∞ ***(Sec. 4.3)*** These searches have now identified many extrasolar planets, although only a few planets comparable in mass to Earth have so far been detected. ∞ ***(Sec. 4.4)*** It is ironic that the first Earth-sized planets found outside the solar system orbit a dead star and have little or nothing to do with our own world.

13.4 Gamma-Ray Bursts

Discovered serendipitously in the late 1960s by military satellites looking for violations of the Nuclear Test Ban Treaty, and first made public in the 1970s, **gamma-ray bursts** consist of bright, irregular flashes of gamma rays typically lasting only a few seconds (Figure 13.10a). Until the 1990s it was thought that gamma-ray bursts were basically "scaled-up" versions of X-ray bursters, in which even more violent nuclear events released more energetic gamma rays. However, that is not the case.

Distances and Luminosities

Figure 13.10(b) shows an all-sky plot of the positions of 2704 bursts detected by the *Compton Gamma-Ray Observatory (CGRO)* during its 9-year operational lifetime. ∞ ***(Sec. 3.5)*** On average, *CGRO* detected gamma-ray bursts at the rate of about one per day. Note that the bursts are distributed uniformly across the sky, rather than being confined to the relatively narrow band of the Milky Way (compare Figure 3.30). This widespread distribution convinced most astronomers that the bursts do not originate within our own Galaxy, as had previously been assumed, but instead are produced at much greater distances.

Measuring the distance to a gamma-ray burst is no easy task. The gamma-ray observations do not provide enough information in and of themselves to tell us how far away the burst is, so astronomers must instead associate the burst with some other object in the sky—called the burst

◀ **FIGURE 13.10 Gamma-Ray Bursts** (a) Plots of intensity versus time for three gamma-ray bursts show that some of them are irregular and spiky, whereas others are much more smoothly varying. (b) Positions on the sky of all the gamma-ray bursts detected by the *Compton Gamma-Ray Observatory* during its 9 years of operation in orbit. The bursts appear to be distributed uniformly across the entire sky, which is mapped here with the plane of the Milky Way running horizontally across its center. *(NASA)* *counterpart*—whose distance can be measured by other means. The techniques for studying counterparts generally involve observations in the optical or X-ray parts of the electromagnetic spectrum. The problem is that the resolution of a gamma-ray telescope is quite poor, so burst positions are uncertain by up to 1 degree, and a relatively large region of the sky must be scanned in search of a counterpart. *(Sec. 3.5)* In addition, the "afterglow" of a burst at X-ray or optical wavelengths fades quite rapidly, severely limiting the time available to complete the search (see Figures 13.11a and b).

The most successful searches for burst counterparts have been carried out by satellites combining gamma-ray detectors with X-ray and/or optical telescopes. For example, NASA's *Swift* mission, launched in 2004 and still (as of 2015) operational, combines a wide-angle gamma-ray detector (to monitor as much of the sky as possible) with two telescopes: one X-ray and one optical/ultraviolet instrument. The gamma-ray detector system pinpoints the direction of the burst to an accuracy of about 4 arc minutes, and within seconds the onboard computer automatically repositions the satellite to point the X-ray and optical telescopes in that direction. At the same time, the craft relays the burst position to other instruments in space and on the ground. *Swift* detects burst counterparts at the rate of about one per week and has played a pivotal role in advancing our understanding of these violent phenomena. Figures 13.11(c) and (d) show *Swift* X-ray and optical images of GRB 080319B, one of the brightest bursts to date. Automated observations at many wavelengths began within seconds of *Swift's* detection, making this burst one of the most intensively studied on record.

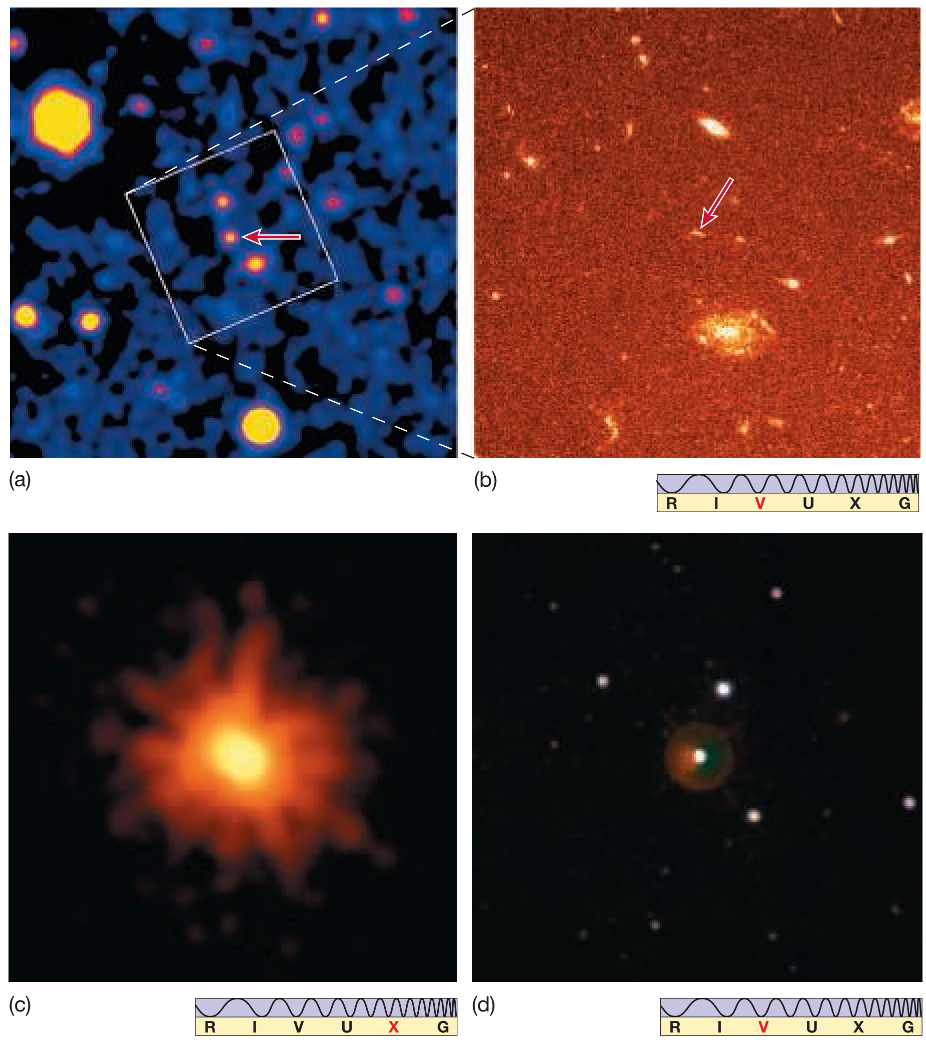
The first direct measurement of the distance to a gamma-ray burst was made in 1997 when astronomers detected the visible afterglow created as the burst faded and cooled. Using spectroscopic distance-measurement techniques (to be discussed in more detail in Section 16.1, they found that the event occurred more than 2 billion parsecs from Earth. Figure 13.11 shows an optical image of another gamma-ray burst, this one almost 5 billion parsecs distant, along with what may be its host galaxy; this is one of the first images to associate a burst with a possible galactic host. To date, the distances to hundreds of gamma-ray bursts have been measured from their afterglows. All are very large, implying that the bursts must be extremely energetic, otherwise they wouldn't be detectable by our equipment.

By the late 1990s, detection techniques had improved to the point that astronomers could locate and study both the rapidly fading afterglows and the faint host galaxies of many gamma-ray bursts. They were then able to measure the distances to these violent events. Distances to several hundred gamma-ray bursts are currently known. As suggested by the bursts' distribution on the sky, *all* of the measured distances are very large—typically billions of parsecs. The two bursts shown in Figure 13.11 lie, respectively, 3.6 and 2.3 billion parsecs away.

These large distances imply that the bursts must be very energetic, since otherwise we wouldn't be able to detect them. But when astronomers tried to estimate the total energy emitted using the inverse-square law, they ran into a

CONCEPT CHECK

What is the connection between X-ray sources and millisecond pulsars?



▲ **FIGURE 13.11 Gamma-Ray Burst Counterpart** (a) Optical image of the gamma-ray burst GRB 971214 taken by the Keck telescope, shows the bright visible afterglow of the gamma-ray source (arrow). (b) By the time this *Hubble* image was taken 2 months later, the afterglow had faded, but a faint image of a host galaxy remains. (c and d) Another long-duration gamma-ray burst, GRB 080319B, was one of the brightest yet observed. Its light was emitted 7.5 billion years ago, yet for a few seconds the flash would have been visible to the unaided eye—if anyone had been looking in just the right spot! Only moments after detonation, it was observed in X-rays (c) and in visible light (d). *(Keck; NASA; ESO)* problem. (Sec. 10.2) If they assumed that the gamma rays were emitted equally in all directions, they found that each burst would generate more energy—in some cases hundreds of times more energy—than a typical supernova explosion, all in a matter of seconds! Such an immense amount of power seemed to defy the laws of physics. However, if the energy is emitted as a *jet*, as most experts now think, then the overall luminosity of the burst is reduced to much more manageable levels, as the energy we see is representative of only a small fraction of the sky, making the energetics of the brightest bursts easier to understand.

As an analogy, consider a handheld laser pointer of the sort commonly used in talks and lectures. It radiates only a few milliwatts of power, much less than a household lightbulb, but it appears enormously bright if you happen to look directly into the beam. (*Don't* do this, by the way!) The laser beam is bright because all of its energy is concentrated in almost a single direction instead of being radiated in all directions into space.

ANIMATION/VIDEO
Colliding Binary Neutron Stars

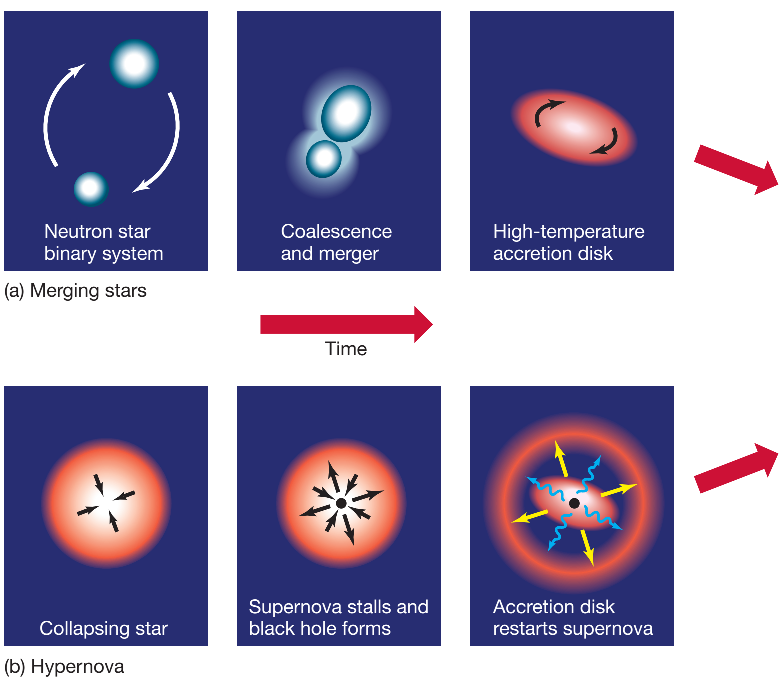
What Causes the Bursts?

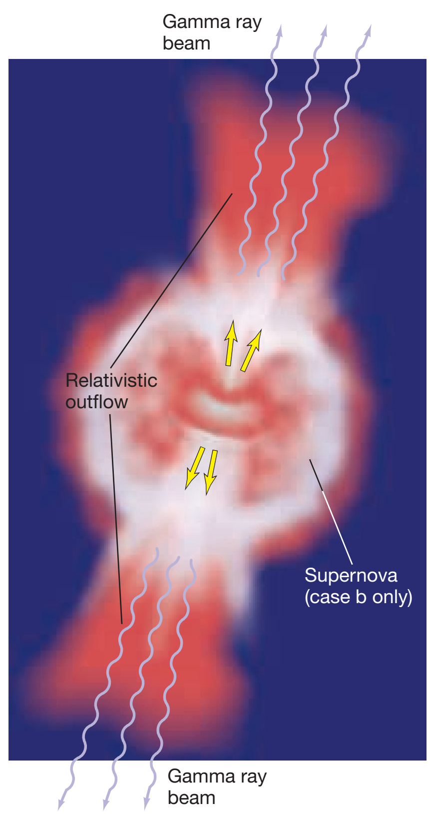
Not only are gamma-ray burst sources extremely energetic, they are also very *small*. The millisecond flickering in the bursting gamma rays detected by [*CGRO*] implies that whatever their origin, all of their energy must come from a volume no larger than a few hundred kilometers across. The reasoning is as follows: If the emitting region were, say, 300,000 km—1 light-second—across, even an instantaneous change in intensity at the source would be smeared out over a time interval of 1 s as seen from Earth, because light from the far side of the object would take 1 s longer to reach us than light from the near side. For the gamma-ray variation not to be blurred by the light-travel time, the source cannot be more than 1 light-millisecond, or 300 km, in diameter.

Theoretical models of gamma-ray bursts describe the burst as a *relativistic fireball*—an expanding jet of superhot gas radiating furiously in the gamma-ray part of the spectrum. (The term "relativistic" here means that the gas particles are moving at speeds comparable to the speed of light, and Einstein's theory of relativity is needed to describe them—see Section 13.6.) The complex burst structure and afterglows we see are produced as the fireball expands, cools, and interacts with its surroundings.

Two leading models for the energy source have emerged. The first (Figure 13.12a) is the "true" end point of a binary star system. Suppose that both members of the binary become neutron stars. As the system continues to evolve, gravitational radiation

▼ **FIGURE 13.12 Gamma-Ray Burst Models** Two models have been proposed to explain gamma-ray bursts. Part (a) depicts the merger of two neutron stars; part (b) shows the collapse of a single star. Both models predict (at right) a relativistic fireball, perhaps releasing energy in the form of jets, as shown.





13.1 DISCOVERY

Gravity Waves—A New Window on the Universe

Electromagnetic waves are common everyday phenomena. They involve periodic changes in the strengths of electric and magnetic fields. ∞ *(Fig. 2.6)* They move through space and transport energy. Any accelerating charged particle, such as an electron in a broadcasting antenna or on the surface of a star, generates electromagnetic waves.

The modern theory of gravity—Einstein's theory of relativity—also predicts waves that move through space. A *gravity wave* is the gravitational counterpart of an electromagnetic wave. *Gravitational radiation* results from changes in the strength of a gravitational field. In theory, any time an object having any mass accelerates, a gravity wave is emitted at the speed of light. The passage of a gravity wave should produce small distortions in the space through which it passes. Gravity is an exceedingly weak force compared with electromagnetism, so these distortions are expected to be very small—in fact, much smaller than the diameter of an atomic nucleus for waves that might be produced by any known astrophysical source. Yet many researchers think that these tiny distortions should be measurable. No experiment has yet succeeded in detecting gravity waves, but their detection would provide such strong support for the theory of relativity that scientists are eager to find them.

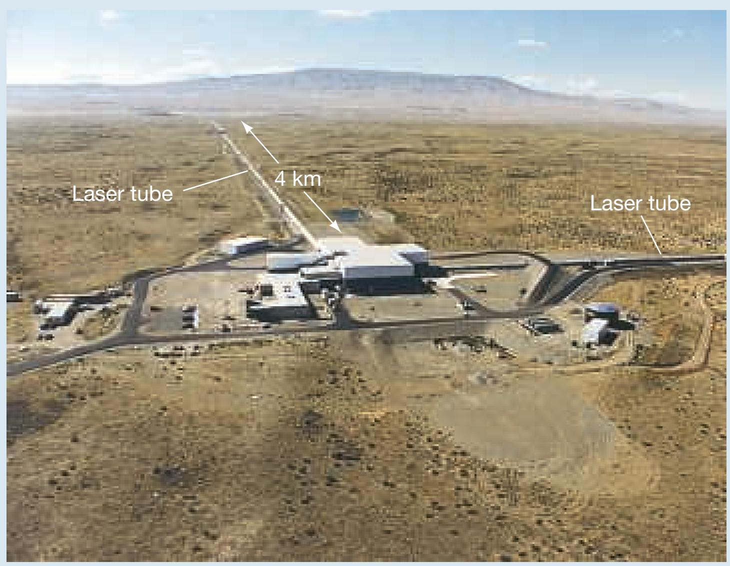
The leading candidates for systems likely to produce gravity waves detectable on Earth include (1) close binary systems containing black holes, neutron stars, or white dwarfs and (2) the collapse of a star into a black hole. Each of these possibilities involves the acceleration of huge masses, resulting in rapidly changing gravitational fields. The first probably presents the best chance to detect gravity waves. Binary star systems should emit gravitational radiation as the component stars orbit one another. As energy escapes in the form of gravity waves, the two stars spiral toward one another, orbiting more rapidly and emitting even more gravitational radiation. For sufficiently close systems, the stars merge in a few tens or hundreds of millions of years (although most of the radiation is emitted during the last few seconds). As we saw in Section 13.4, neutron star mergers may well also be the origin of some gamma-ray bursts, so gravitational radiation might provide an alternative means of studying these violent and mysterious phenomena.

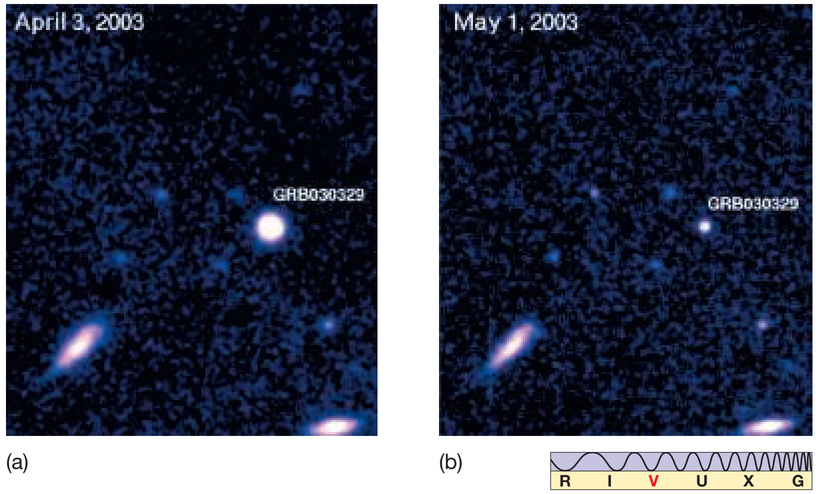
Such a slow but steady decay in the orbit of a binary system has in fact been detected. In 1974, radio astronomer Joseph Taylor and graduate student Russell Hulse at the University of Massachusetts discovered a very unusual binary system. Both components are neutron stars, and one is observable from Earth as a pulsar. This system has become known as the *binary pulsar.* Measurements of the periodic Doppler shift of the pulsar's radiation show that its orbit is slowly shrinking at exactly the rate predicted by relativity theory if the energy were being carried off by gravity waves. Even though the gravity waves themselves have not been detected, the binary pulsar is regarded by most astronomers as very strong evidence supporting general relativity. Taylor and Hulse received the 1993 Nobel Prize in Physics for their discovery.

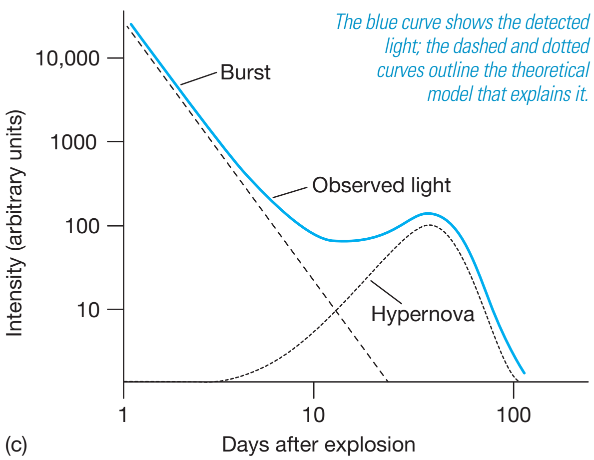
In 2004, radio astronomers announced the discovery of a *double-pulsar* binary system with an even shorter period than the binary pulsar, implying stronger relativistic effects and a shorter merger time—less than 100 million years. Because both components are pulsars and the system, by pure luck, also happens to be seen almost exactly edge on by observers on Earth, leading to eclipses, this system has provided a wealth of information on both neutron stars and gravitational physics.

The figure below shows part of an ambitious gravity-wave observatory called LIGO—short for Laser Interferometric Gravity-Wave Observatory—which became operational in 2003. Twin detectors, one (shown here) in Hanford, Washington, the other in Livingston, Louisiana, use laser beams to measure the extremely small (less than one-thousandth the diameter of an atomic nucleus) distortions of space produced in the lengths of the 4-km-long arms should a gravity wave pass by. The instruments are in theory capable of detecting waves from many Galactic and extragalactic sources, although, so far, no gravity waves have actually been detected, despite upgrades in 2010 and 2015 that boosted the detector's sensitivity by more than a factor of 20.

If these experiments are successful, the discovery of gravity waves could herald a new age in astronomy, in much the same way that invisible electromagnetic waves, virtually unexplored a century ago, revolutionized classical astronomy and led to the field of modern astrophysics.







◂ **FIGURE 13.13 Hypernova?** The gamma-ray burst GRB 030329 may prove crucial to theorists' understanding of the physical processes underlying these violent phenomena. First detected by the *High Energy Transient Explorer 2* satellite and subsequently observed at radio, optical, and X-ray wavelengths, the burst counterpart has all the hallmarks of a high-mass supernova, lending strong support to the hypernova model. Here, the counterpart is shown (a) near the moment of the burst and (b) fading a month later. (c) This graph shows details of the emitted radiation from another, but similar, gamma-ray burst. *(ESO)*

(see *Discovery 13-1*) is released, and the two ultradense stars spiral in toward each other. Once they are within a few kilometers of one another, coalescence is inevitable. Such a merger will likely produce a violent explosion comparable in energy to a supernova, and energetic enough to explain the flashes of gamma rays we observe. The overall rotation of the binary system may channel the energy into a high-speed, high-temperature jet.

The second model (Figure 13.12b), sometimes called a *hypernova,* is a "failed" supernova—but what a failure! In this picture a very massive star undergoes core collapse just as described earlier for a Type II supernova, but instead of forming a neutron star, the core collapses in on itself, forming a black hole (see Section 13.5). ∞ ***(Sec. 12.4)*** Instead of being blown to pieces, the star implodes onto the black hole, forming an accretion disk and again generating a relativistic jet. The jet punches its way out of the star, producing a gamma-ray burst as it slams into the surrounding shells of gas expelled from the star during the final stages of its nuclear-burning lifetime. At the same time, intense radiation from the accretion disk may restart the stalled supernova, blasting what remains of the star into space.

The idea of a relativistic fireball has become widely accepted among workers in this branch of astrophysics. Most researchers regard it as likely that the energy is released as a jet and that the most intense gamma-ray bursts occur when the jet is directed toward us ("looking into the laser"). Which of the two models just described is correct? Experts in the field would say that the answer is probably *both.* The hypernova model predicts bursts of relatively long duration and is the leading explanation of the "long" gamma-ray bursts lasting more than about 2 s. Detailed calculations indicate that the neutron star merger model can naturally account for the shorter bursts. Thus, both of the scenarios depicted in Figure 13.12 contribute to the total.

Thanks to the "rapid response network" provided by *Swift* and other instruments, astronomers now have detailed observations of many afterglows of both types of burst. Figures 13.13(a) and (b) show the afterglow of the long burst GRB 030329, as seen by the 8.2-m VLT in Chile. ∞ ***(Sec. 3.2)*** Both the spectrum and the light curve were consistent with what astronomers expected from the supernova of a very massive (roughly 25-solar mass) star. ∞ ***(Sec. 12.4)*** Figure 13.13(c) shows a simplified light curve of another burst, illustrating how the "burst" and "hypernova" components can be distinguished.

The rapidly fading X-ray afterglows from the short bursts are consistent with the predictions of the neutron star merger scenario. Very recent observations also reveal that a few of these bursts may actually involve the theoretically predicted, but rare, merger between a neutron star and a black hole, which should have its own characteristic light signature.

CONCEPT CHECK

What are gamma-ray bursts, and why did they pose such a challenge to theory?

13.5 Black Holes

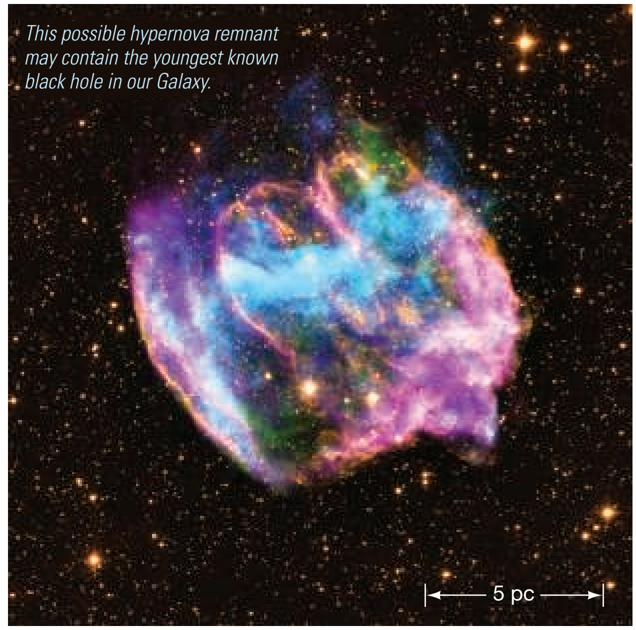
Neutron stars are supported by the resistance of tightly packed neutrons to further compression. Squeezed together, these elementary particles form a hard ball of ultradense matter that not even gravity can compress further. Or do they? Is it possible that, given enough matter packed into a small enough volume, the collective pull of gravity can eventually crush even a neutron star? Can gravity continue to compress a massive star into an object the size of a planet, a city, a pinhead—even smaller? The answer, apparently, is yes.

The Final Stage of Stellar Evolution

Although the precise figure is uncertain, mainly because the behavior of matter at very high densities is not well understood, most researchers concur that the mass of a neutron star cannot exceed about three times the mass of the Sun. This is the neutron star equivalent of the white dwarf mass limit discussed in the previous chapter. ∞ *(Sec. 12.5)* Above this mass, not even tightly packed neutrons can withstand the star's gravitational pull. In fact, we know of *no* force that can counteract gravity beyond this point. Thus, if enough material is left behind after a supernova or hypernova explosion that the central core exceeds this limit, or if enough matter falls back onto the neutron star after the supernova has occurred, gravity wins the battle with pressure once and for all, and the central core collapses forever. Stellar evolution theory indicates that this is the fate of any star whose main-sequence mass exceeds about 25 times the mass of the Sun.

As the core shrinks, the gravitational pull in its vicinity eventually becomes so great that nothing—not even light—can escape. The resultant object therefore emits no light, no other form of radiation, no information whatsoever. Astronomers call this bizarre end point of stellar evolution, in which the core of a very-high-mass star collapses in on itself and vanishes forever, a **black hole.**

Black holes are much rarer than neutron stars, simply because very few stars have enough mass to form black holes. Nevertheless, astronomers think they have evidence for at least one relatively recent hypernova in our Galaxy that produced a black hole. Figure 13.14 shows W49B, a Galactic supernova remnant whose asymmetric shape and anomalous heavy element composition are consistent with the predictions of hypernova models of massive stars, and careful observations reveal no evidence of a neutron star. If these observations hold up, then W49B may contain the youngest known black hole in our Galaxy, formed just 1000 years ago.



▲ **FIGURE 13.14** **Hypernova Remnant?** This is a composite X-ray, infrared, and optical image of W49B, a supernova remnant lying some 8000 pc away. Its distorted, asymmetric shape and unusual composition suggest to many astronomers that this is actually the remnant of a hypernova—a gamma-ray burst in our own Galaxy—perhaps 1000 years old and containing a black hole. *(NASA)*

Escape Speed

Newtonian mechanics—until now our indispensable guide to the universe—cannot adequately describe conditions in or near black holes. ∞ *(Sec. 1.4)* To comprehend these collapsed objects, we must turn instead to the modern theory of gravity, Einstein's **general theory of relativity,** discussed in Section 13.6. Still, we can usefully describe some aspects of these strange bodies in more or less Newtonian terms. Let's reconsider the familiar Newtonian concept of escape speed—the speed needed for one object to escape the gravitational pull of another—supplemented by two key facts from relativity: (1) nothing can travel faster than light and (2) all things, *including light,* are attracted by gravity.

A body's escape speed is proportional to the square root of the body's mass divided by the square root of its radius (see *More Precisely 5-1)*. Earth's radius is 6400 km and the escape speed from Earth's surface is just over 11 km/s. Now consider a hypothetical experiment in which Earth is squeezed on all sides by a gigantic vise. As our planet shrinks under the pressure, the escape speed increases because the radius is decreasing. Suppose Earth were compressed to one-fourth its present size. The escape speed would double (because $1/\sqrt{1/4} = 2$). To escape from this compressed Earth, an object would need a speed of at least 22 km/s.

Imagine compressing Earth by an additional factor of 1000, making its radius hardly more than a kilometer. Now a speed of about 700 km/s—more than the escape speed of the Sun—would be needed to escape. Compress Earth still further, and the escape speed continues to rise. If our hypothetical vise were to squeeze Earth hard enough to crush its radius to about a centimeter, the speed needed to escape its surface would reach 300,000 km/s. But this is no ordinary speed. It is the speed of light, c, the fastest speed allowed by the laws of physics as we currently know them.

Thus, if by some fantastic means the entire planet Earth could be compressed to less than the size of a grape, the escape speed would exceed the speed of light. And because nothing can exceed that speed, the compelling conclusion is that nothing—absolutely nothing—could escape from the surface of such a compressed body. Even radiation—radio waves, visible light, X-rays, photons of all wavelengths—would be unable to escape its intense gravity. Our planet would be invisible and uncommunicative—no signal of any sort could be sent to the universe outside. The origin of the term *black hole* becomes clear. For all practical purposes, Earth could be said to have disappeared from the universe. Only its gravitational field would remain behind, betraying the presence of its mass, now shrunk to a point.

The Event Horizon

Astronomers have a special name for the critical radius at which the escape speed from an object would equal the speed of light and within which the object could no longer be seen. It is the **Schwarzschild radius,** after Karl Schwarzschild, the German scientist who first studied its properties. The Schwarzschild radius of any object is proportional to its mass. For Earth, it is 1 cm. For Jupiter, at about 300 Earth masses, it is about 3 m. For the Sun, at 300,000 Earth masses, it is 3 km. For a 3-solar-mass stellar core, the Schwarzschild radius is about 9 km. As a convenient rule of thumb, the Schwarzschild radius of an object is simply 3 km multiplied by the object's mass measured in solar masses.

SELF-GUIDED TUTORIAL MA
Escape Speed and Black Hole Event Horizons

Every object has a Schwarzschild radius—it is the radius to which the object would have to be compressed for it to become a black hole. Put another way, a black hole is an object that happens to lie within its own Schwarzschild radius. The surface of an imaginary sphere having a radius equal to the Schwarzschild radius and centered on a collapsing star is called the **event horizon.** No event occurring within this region can ever be seen, heard, or known by anyone outside. Even though there is no matter of any sort associated with it, we can think of the event horizon as the "surface" of a black hole.

Theory indicates that, if more than 3 solar masses of material remain behind after a supernova explosion, the remnant core will collapse catastrophically, diving below the event horizon in much less than a second. The event horizon is not a physical boundary of any kind—just a communications barrier. The core would shrink right past the Schwarzschild radius to ever-diminishing size on its way to being crushed to a point. It simply "winks out," disappearing and becoming a small dark region from which nothing can escape—a literal black hole in space. This is the predicted fate of stars having more than about 20–25 times the mass of the Sun.

CONCEPT CHECK

What happens if you compress an object within its own Schwarzschild radius?

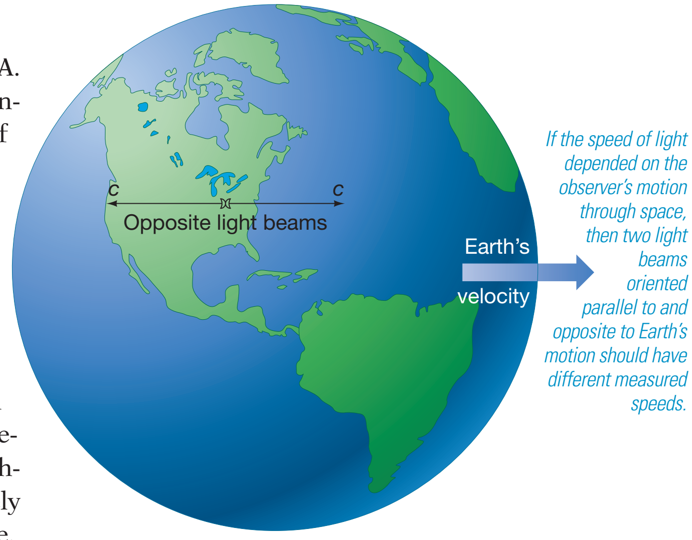
13.6 Einstein's Theories of Relativity

By the latter part of the 19th century, physicists were well aware of the special status of the speed of light, c. It was, they knew, the speed at which all electromagnetic waves traveled, and, as best they could tell, it represented an upper limit on the speeds of *all* known particles. Scientists struggled without success to construct a theory of mechanics and radiation in which c was a natural speed limit.

Special Relativity

In 1887, a fundamental experiment carried out by American physicists A. A. Michelson and E. W. Morley compounded theorists' problems further by demonstrating another important aspect of light: The measured speed of a beam of light is *independent* of the motion of either the observer or the source.

Michelson and Morley attempted to determine Earth's motion relative to the "absolute" space in which light supposedly moved by measuring the speed of light at different times of the day (so that the orientation of their equipment would change as Earth rotated) and on different days of the year (so that Earth's velocity would vary as our planet orbited the Sun). As illustrated in Figure 13.15, they expected to measure a faster-moving beam of light when it was traveling opposite to Earth's motion (to the left in the figure) and a slower beam when Earth was "catching up" on it (to the right). But in fact they measured precisely the *same* velocity for any orientation of their apparatus. Far from establishing the properties of absolute space, the Michelson–Morley experiment ultimately demolished the entire concept—and with it, the 19th-century view of the universe.



▲ **FIGURE 13.15 Michelson–Morley Experiment** If light propagates at a fixed speed through space, then common sense suggests that the speed of a beam of light should depend on Earth's velocity. The Michelson–Morley experiment tried but failed to measure this dependence and in the process ushered in the era of modern physics.

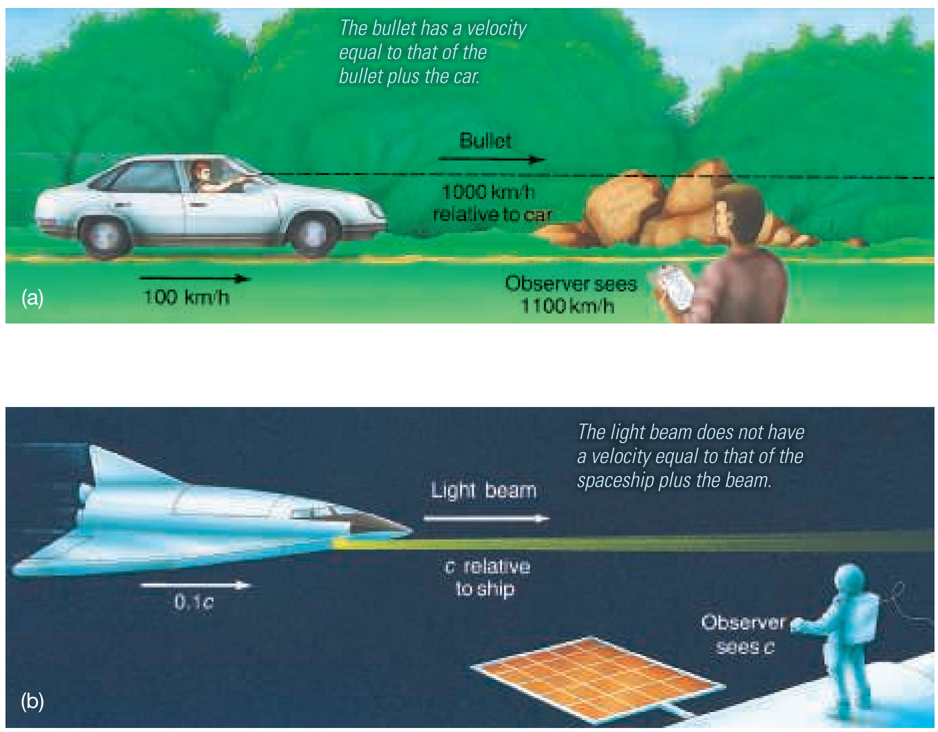
MA INTERACTIVE
Exploring the Effects of Relative Motion

All subsequent experiments confirm that no matter what our motion may be relative to the source of the radiation, we always measure precisely the same value for *c:* 299,792.458 km/s. A moment's thought tells us that this is a decidedly nonintuitive statement. For example, if we were traveling in a car moving at 100 km/h and we fired a bullet forward with a speed of 1000 km/h relative to the car, an observer standing at the side of the road would see the bullet pass by at 100 + 1000 = 1100 km/h, as illustrated in Figure 13.16(a). However, the Michelson–Morley experiment tells us that if we were traveling in a rocket ship at one-tenth the speed of light, 0.1*c*, and we shone a searchlight beam ahead of us (Figure 13.16b), an outside observer would measure the speed of the beam not as 1.1*c*, as the example of the bullet would suggest, but as *c*. The rules that apply to particles moving at or near the speed of light are different from those we are used to in everyday life.

The *special theory of relativity,* or just *special relativity,* was proposed by Einstein in 1905 to deal with the preferred status of the speed of light. The theory is the mathematical framework that allows us to extend the familiar laws of physics from low speeds (i.e., speeds much less than *c,* which are often referred to as *nonrelativistic*) to very high (or *relativistic*) speeds, comparable to *c*.

The essential features of special relativity are:

1. The speed of light, *c,* is the maximum possible speed in the universe, and all observers measure the *same* value for *c,* regardless of their motion. Einstein broadened this statement into the *principle of relativity*: The basic laws of physics are *the same* to all observers.
3. There is *no* absolute frame of reference in the universe; that is, there is no "preferred" observer relative to whom all other velocities can be measured. Instead, only relative velocities between observers matter (hence the term "relativity").
3. Neither space nor time can be considered independently of one another. Rather, they are each components of a single entity: *spacetime*. There is no absolute, universal time—observers' clocks tick at different rates, depending on the observers' motions relative to one another.



▲ **FIGURE 13.16 Speed of Light** (a) A bullet fired from a speeding car is measured by an outside observer to have a speed equal to the sum of the speeds of the car and of the bullet. (b) A beam of light shining forward from a high-speed spacecraft is still observed to have speed *c,* regardless of the speed of the spacecraft. The speed of light is thus independent of the speed of the source or of the observer.

Special relativity is equivalent to Newtonian mechanics in describing objects that move much more slowly than the speed of light, but it differs greatly in its

13.1 MORE PRECISELY

Special Relativity

Einstein's theory of special relativity was constructed in large part to solve the puzzle of the 1887 Michelson–Morley experiment (see Section 13.6), which demonstrated that the observed speed of light is *independent* of the observer's motion through space. Einstein elevated the speed of light to the status of a constant of nature, rewrote the laws of mechanics to reflect that new fact, and opened the door to a flood of new physics and a much deeper understanding of the universe. But many commonsense ideas had to be abandoned in the process and replaced with some decidedly less-intuitive concepts. We describe here some of those odd consequences of Einstein's theory.

Imagine that you are an observer watching a rocket ship fly past at relative velocity v and that the craft is close enough for you to make detailed observations of the inside of its cabin. If v is much less than the speed of light, c, you would see nothing out of the ordinary—special relativity is consistent with familiar Newtonian mechanics at low velocities. However, if v is comparable to c, unexpected things start to happen.

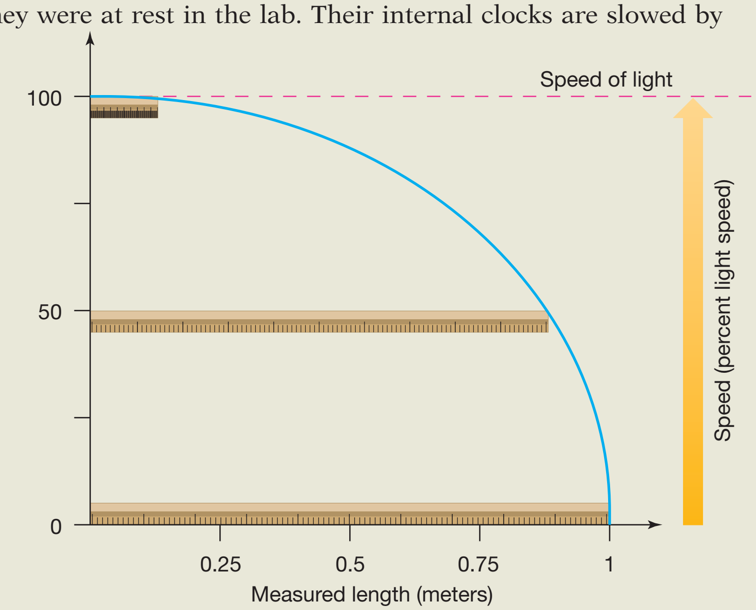
As the ship's velocity increases, you begin to notice that the ship appears to *contract* in the direction in which it is moving. A meterstick on board, identical at launch to the one you keep in your laboratory, is now shorter than its twin. This is called *Lorentz contraction* (or sometimes Lorentz–Fitzgerald contraction). The first figure shows the stick's measured length aboard the moving ship: At low velocities (bottom) the meterstick measures 1 m, but at high velocities (top), the stick is shortened considerably. Because of Lorentz contraction, a meterstick moving at 90 percent of the velocity of light would shrink to a little less than half a meter. (This is not an optical illusion.)

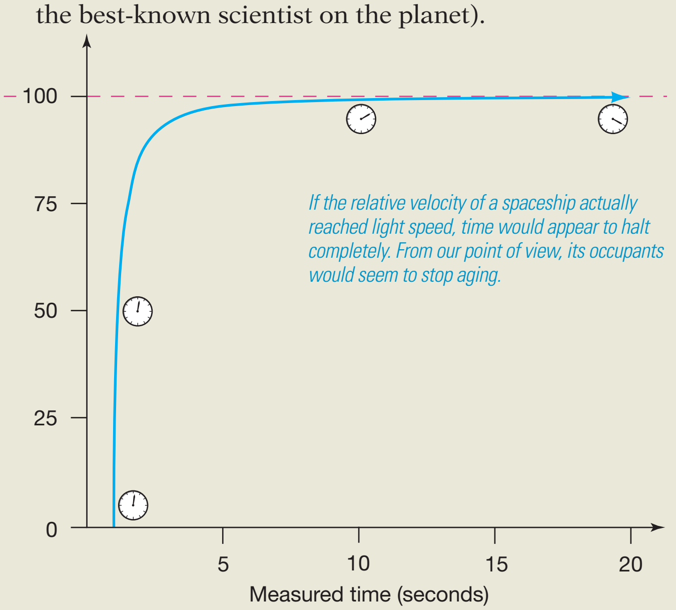
At the same time, the ship's clock, synchronized prior to launch with your own, now ticks *more slowly* (second figure). This phenomenon, known as *time dilation*, has been observed many times in laboratory experiments in which fast-moving radioactive particles are observed to decay more slowly than if they were at rest in the lab. Their internal clocks are slowed by their rapid motion. Although no material particle can actually reach the speed of light, Einstein's theory implies that, as v approaches c, the measured length of the meterstick will shrink to nearly zero and the clock will slow to a virtual stop.

Of course, from the point of view of an astronaut on board the spaceship, *you* are the one moving rapidly. Hence, as seen from the ship, *you* appear to be compressed in the direction of motion, and *your* clock runs slowly! How can both observations be correct? After all, you both know that nothing has happened to your metersticks or clocks. You feel no force squeezing your bodies. What is going on?

When measuring the length of the moving meterstick, you do so by noting the positions of the two ends *at the same time, according to your clock*. But those two events—the two measurements you make—do *not* occur at the same time as seen by the astronaut on the spaceship. In relativity, time is relative, and simultaneity (the idea that two events happen "at the same time") is no longer a well-defined concept. From the astronaut's viewpoint, your measurement of the leading end of the meterstick occurs *before* your measurement of the trailing end. This time discrepancy ultimately results in the Lorentz contraction you observe. A similar argument applies to measurements of time, such as the period between two clock ticks. Time dilation occurs because the measurements occur at the same location and different times in one frame, but at *different places and times* in the other.

Einstein's ideas were revolutionary at the time, requiring physicists to abandon some long-held, cherished, and "obvious" facts about the universe. Reading the above discussion, you can perhaps begin to understand why special relativity initially encountered such resistance among some scientists (and why it still confuses nonscientists today!). Nevertheless, the gain in scientific understanding ultimately overcame the price in unfamiliarity. Within just a few years, special relativity had become almost universally accepted (and Einstein was well on his way to becoming the best-known scientist on the planet).





predictions at relativistic velocities (see *More Precisely 13-1*). Yet, despite their often nonintuitive nature, all of the theory's predictions have been repeatedly verified to a high degree of accuracy. Today, special relativity lies at the heart of modern science. No scientist seriously doubts its validity.

General Relativity

In constructing his special theory of relativity, Einstein rewrote the laws of motion expounded by Newton more than two centuries previously. ∞ *(Sec. 1.4)* Fitting Newton's other great legacy—the theory of gravitation—into the framework of relativity was a much more complex mathematical problem, which took Einstein another decade to complete. The result once again overturned scientists' conception of the universe.

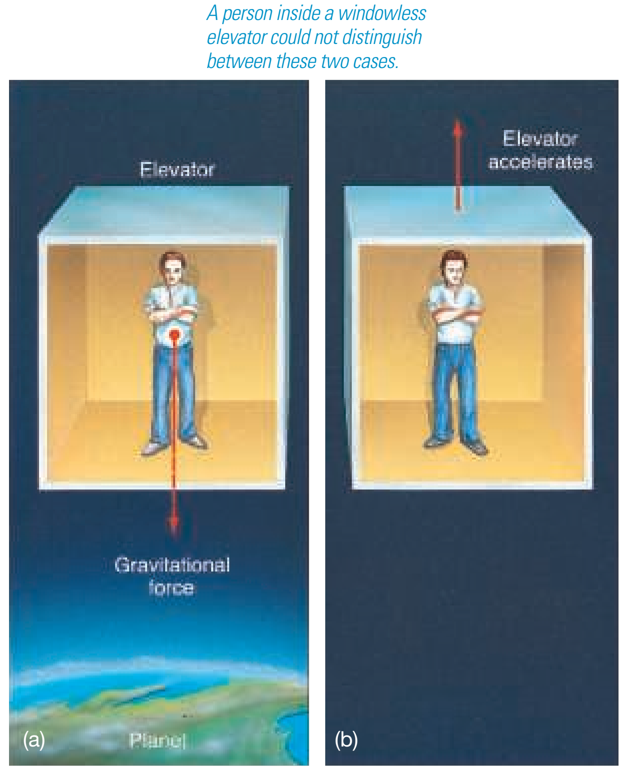
In 1915, Einstein illustrated the connection between special relativity and gravity with the following famous "thought experiment." Imagine that you are enclosed in an elevator with no windows, so that you cannot directly observe the outside world, and the elevator is floating in space. You are weightless. Now suppose that you begin to feel the floor press up against your feet. Weight has apparently returned. There are two possible explanations for this, as shown in Figure 13.17. A large mass could have come nearby, and you are feeling its downward gravitational attraction (Figure 13.17a), *or* the elevator has begun to accelerate upward, and the force you feel is that exerted by the elevator as it accelerates you at the same rate (Figure 13.17b). The crux of Einstein's argument is this: There is *no* experiment that you can perform within the elevator (without looking outside) that will let you distinguish between these two possibilities.

Thus, Einstein reasoned, there is no way to tell the difference between a gravitational field and an accelerated frame of reference (such as the rising elevator in the thought experiment). This statement is known more formally as the *equivalence principle*. Using it, Einstein succeeded in incorporating gravity into special relativity as a general acceleration of all particles. The resulting theory is called *general relativity*. However, Einstein found that another huge conceptual leap was needed. To include the effects of gravity, the mathematics forced Einstein to the unavoidable conclusion that spacetime—the single entity combining space and time, central to special relativity—has to be *curved*.

The central concept of general relativity is this: Matter—all matter—tends to "warp" or curve space in its vicinity. Objects such as planets and stars react to this warping by changing their paths. In the Newtonian view of gravity, particles move on curved trajectories because they are acted upon by a gravitational force. ∞ *(Sec. 1.4)* In Einsteinian relativity, those particles move on curved trajectories because they are falling freely through space, following the curvature of spacetime produced by some nearby massive object. The more the mass, the greater the warping. In general relativity, there is no such thing as a "gravitational force" in the Newtonian sense. Objects move as they do because they follow the curvature of spacetime, which is determined by the amount of matter present. Stated more loosely, in the words of renowned relativist John Archibald Wheeler, "Spacetime tells matter how to move, and matter tells spacetime how to curve."

Some props may help you visualize these ideas. Bear in mind, however, that these props are not real, but only tools to help you grasp some exceedingly strange concepts. Imagine a pool table with the tabletop made of a thin rubber sheet rather than the usual hard felt. As Figure 13.18 suggests, such a rubber sheet becomes distorted when a heavy weight (such as a rock) is placed on it. The heavier the rock (Figure 13.18b), the larger is the distortion.

Trying to play pool on this table, you would quickly find that balls passing near the rock are deflected by the curvature of the tabletop (Figure 13.18b). The



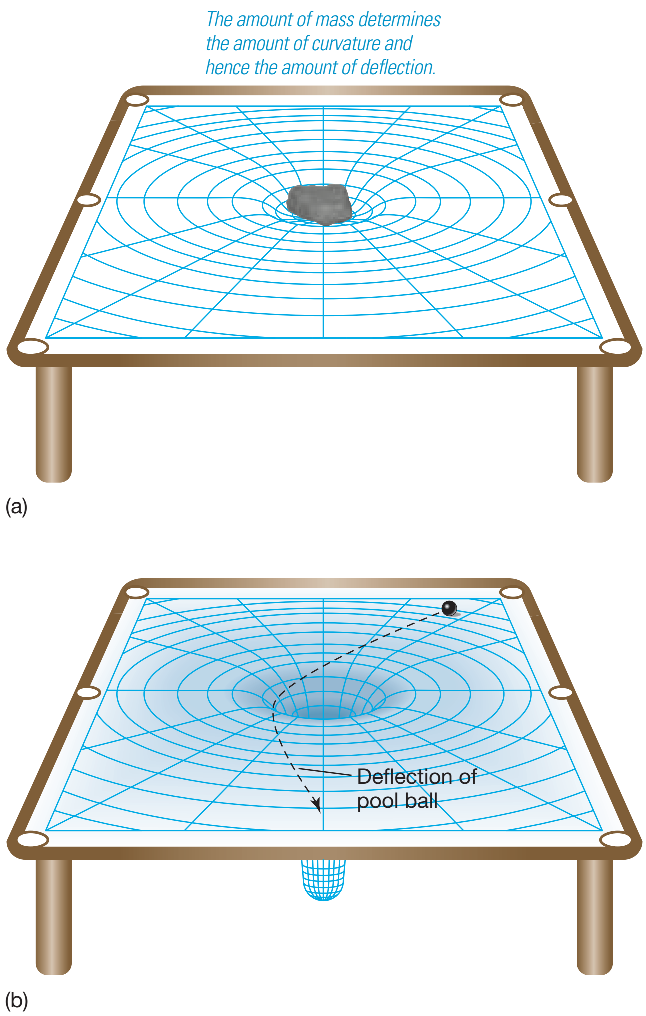
▲ **FIGURE 13.17 Einstein's Elevator** Einstein reasoned that no experiment conducted entirely within an elevator floating in space can tell a passenger whether the force he feels is (a) due to the gravity of a nearby massive object or (b) caused by the acceleration of the elevator itself.

DATA POINTS

Special Relativity

More than 35 percent of students had difficulty describing how special relativity affects the measured properties of fast-moving objects. Some points to remember:

- As you observe a fast-moving spacecraft, it will appear to shrink in the direction of motion, its clock will tick more slowly, and its mass will increase.
- An observer on board the spacecraft will say exactly the same about your size, clock, and mass!
- The resolution of this paradox is that simultaneous measurements in one frame are not simultaneous in another, so that two observers can each see the other's clock apparently running slow without contradiction.



◀ **FIGURE 13.18 Curved Space INTERACTIVE** (a) A pool table made of a thin rubber sheet sags when a weight is placed on it. Likewise, space is bent, or warped, in the vicinity of any massive object. (b) A ball shown rolling across the table is deflected by the curvature of the surface, in much the same way that a planet's curved orbit is determined by the curvature of spacetime produced by the Sun.

pool balls are not attracted to the rock in any way; rather, they respond to the curvature of the sheet produced by the rock's presence. In much the same way, anything that moves through space—matter *or radiation*—is deflected by the curvature of spacetime near a star. (See *More Precisely 13-2* for a solar system measurement, and Sections 14.6 and 16.3 for examples on much larger scales.) Earth's orbital path is the trajectory that results as our planet falls freely in the relatively gentle curvature of space created by our Sun. When the curvature is small (i.e., gravity is weak), both Einstein and Newton predict the same orbit—the one we observe. However, as the gravitating mass increases, the two theories begin to diverge.

Curved Space and Black Holes

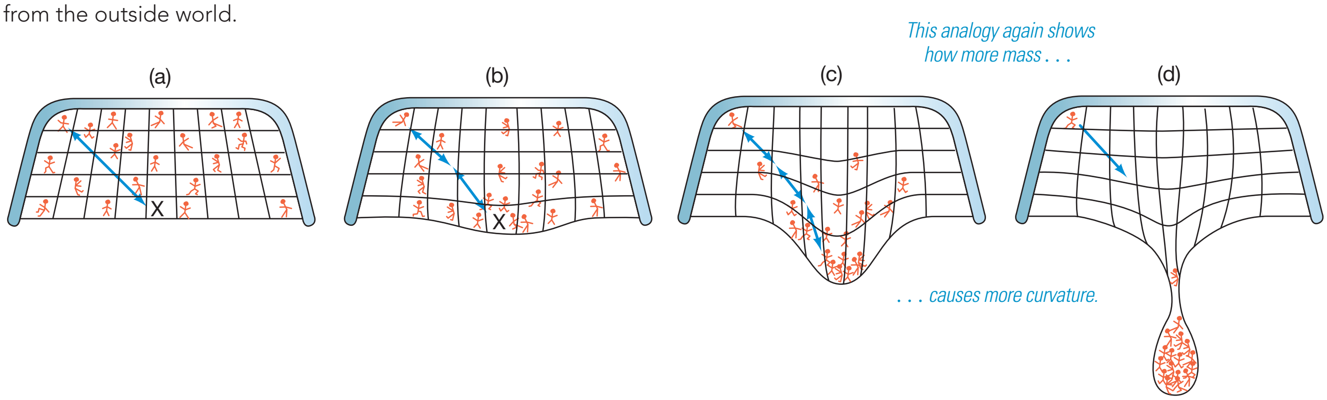
Modern notions about black holes rest squarely on the general theory of relativity. Although white dwarfs and (to a lesser extent) neutron stars can be adequately described by the classical Newtonian theory of gravity, only the modern Einsteinian theory of relativity can properly account for the bizarre physical properties of black holes.

Let's consider another analogy. Imagine a large extended family of people living on a huge rubber sheet—a sort of gigantic trampoline. Deciding to hold a reunion, they converge on a given place at a given time. As shown in Figure 13.19, one person remains behind, not wishing to attend. She keeps in touch with her relatives by means of "message balls" rolled out to her (and back from her) along the surface of the sheet. These message balls are the analog of radiation carrying information through space.

As the people converge, the rubber sheet sags more and more. Their accumulating mass creates an increasing amount of space curvature. The message balls can still reach the lone person far away in nearly flat space, but they arrive less frequently as the sheet becomes more and more warped and stretched—as shown in Figures 13.19(b) and (c)—and the balls have to climb out of a deeper and deeper well. Finally, when enough people have arrived at the appointed spot, the mass becomes too great for the rubber to support them. As illustrated in Figure 13.19(d), the sheet pinches off into a "bubble," compressing the people into oblivion and severing their communications with the lone survivor outside. This final stage represents the formation of an event horizon around the reunion party.

Right up to the end—the pinching off of the bubble—two-way communication is possible. Message balls can reach the outside from within (but at a slower and slower rate as the rubber stretches), and messages from outside can get in without difficulty. However, once the event horizon (the bubble) forms, balls from the outside can still fall in, but they can no longer be sent back out to the person left behind, no

▼ **FIGURE 13.19 Space Warping** Mass causes a rubber sheet (or space) to be curved. As people assemble at a fixed spot on the sheet (marked by an "×"), the curvature grows larger, as shown in (a)–(c). The blue arrows represent some directions in which information can be sent from place to place. (d) The people are eventually sealed inside the bubble, forever trapped and cut off from the outside world.



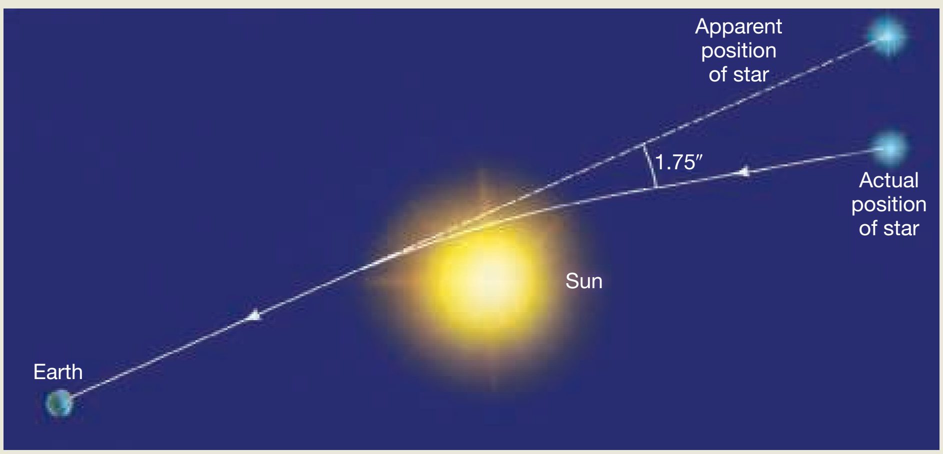
13.2 MORE PRECISELY

Tests of General Relativity

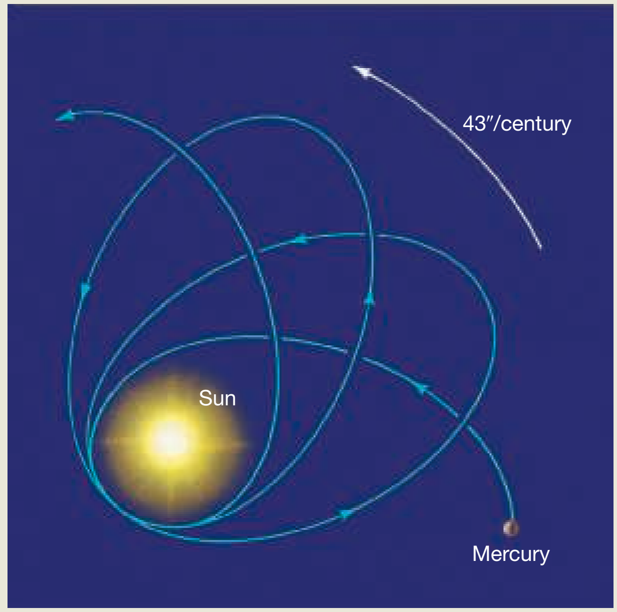
Special relativity is the most thoroughly tested and most accurately verified theory in the history of science. General relativity, however, is on somewhat less firm experimental ground. The problem with verifying general relativity is that its effects on Earth and in the solar system—the places where we can most easily perform tests—are very small. Just as special relativity produces major departures from Newtonian mechanics only when speeds approach the speed of light, general relativity predicts large departures from Newtonian gravity only when extremely strong gravitational fields are involved.

Here we consider just two "classical" tests of the theory—solar system experiments that helped ensure acceptance of Einstein's theory. Bear in mind, however, that there are no known tests of general relativity in the "strong-field" regime—that part of the theory that predicts black holes, for example—so the full theory has never been experimentally tested.

At the heart of general relativity is the premise that everything, including light, is affected by gravity because of the curvature of spacetime. Shortly after he published his theory in 1915, Einstein noted that light from a star should be deflected by a measurable amount as it passes the Sun. The closer to the Sun the light comes, the more it is deflected. Thus, the maximum deflection should occur for a ray that just grazes the solar surface. Einstein calculated that the deflection angle should be 1.75, a small but detectable amount.



Of course, it is normally impossible to see stars so close to the Sun. During a solar eclipse, however, when the Moon blocks the Sun's light, the observation does become possible, as illustrated in the figure at lower left. In 1919 a team of observers led by British astronomer Sir Arthur Eddington succeeded in measuring the deflection of starlight during an eclipse. The results were in excellent agreement with the prediction of general relativity.



Another prediction of general relativity is that planetary orbits should deviate slightly from the perfect ellipses of Kepler's laws. Again, the effect is greatest where gravity is strongest—that is, closest to the Sun. Thus, the largest relativistic effects are found in the orbit of Mercury. Relativity predicts that Mercury's orbit is not exactly a closed ellipse. Instead, its orbit should rotate slowly, as shown in the second (highly exaggerated) diagram above. The amount of rotation is very small—only per century—but Mercury's orbit is so well charted that even this tiny effect is measurable.

matter how fast they are rolled. They cannot make it past the "lip" of the bubble in Figure 13.19(d). This analogy (very) roughly depicts how a black hole warps space completely around on itself, isolating its interior from the rest of the universe.

The essential ideas—the slowing down and eventual cessation of outward-going signals and the one-way nature of the event horizon once it forms—all have parallels in the case of stellar black holes. In Einsteinian terms, a *black hole* is a region of space where the gravitational field becomes overwhelming and the curvature of space extreme. At the event horizon itself, the curvature is so great that space "folds over" on itself, causing objects within to become trapped and disappear.

PROCESS OF SCIENCE CHECK

How do Newton's and Einstein's theories differ in their descriptions of gravity? Why were scientists initially resistant to Einstein's theories of relativity?

13.7 Space Travel Near Black Holes

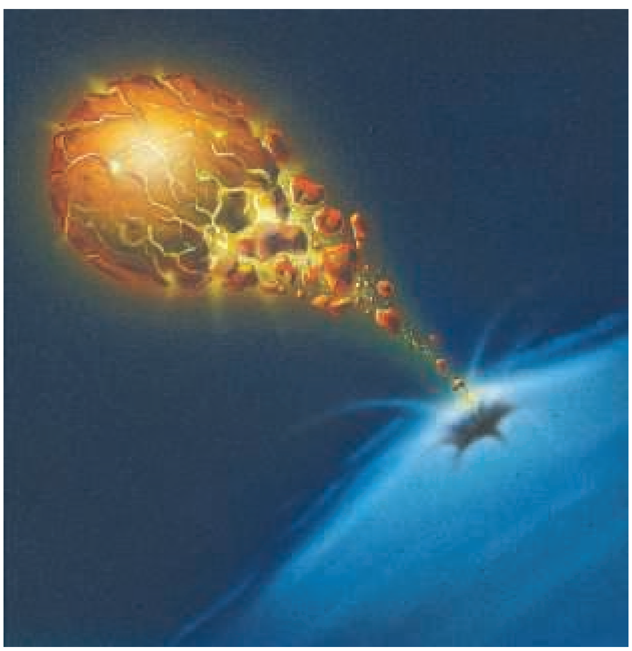
Black holes are *not* cosmic vacuum cleaners. They don't cruise around interstellar space, sucking up everything in sight. The orbit of an object near a black hole is essentially the same as its orbit near a "normal" star of the same mass as the black hole. Only if the object happened to pass within a few Schwarzschild radii (perhaps 50–100 km for a typical 5- to 10-solar-mass black hole formed in a supernova explosion) of the event horizon would there be any significant difference between its actual orbit and the one predicted by Newtonian gravity and described by Kepler's laws. Of course, if some matter did fall into the black hole—that is, if its orbit happened to take it too close to the event horizon—it would be unable to get out. Black holes are like turnstiles, permitting matter to flow in only one direction—inward.

ANIMATION/VIDEO MA
Energy Released from a Black Hole?

Tidal Forces

Matter flowing into a black hole is subject to enormous gravitational stress. An unfortunate explorer falling feet first into a solar mass black hole would find that the pull of gravity is much stronger at her feet (which are closer to the hole) than at her head. This force difference is a *tidal force*—precisely the same basic phenomenon that is responsible for ocean tides on Earth and the spectacular volcanoes on Io—except that the tidal forces at work in and near a black hole are far more powerful than any we are ever likely to find in the solar system. ∞ *(Secs. 5.2, 8.1)* The tidal force due to the black hole is so great that our explorer would be stretched enormously in height and squeezed unmercifully laterally. She would be torn apart long before she reached the event horizon.

The net result of all this stretching and squeezing is numerous and violent collisions among the resulting debris, causing a great deal of frictional heating of any infalling matter. As illustrated (with some artistic license) in Figure 13.20, material is simultaneously torn apart and heated to high temperatures as it plunges into the hole. So efficient is this heating that prior to reaching the hole's event horizon, matter falling into the hole emits radiation of its own accord. For a black hole of roughly solar mass, the energy is expected to be emitted in the form of X-rays. Thus, contrary to what we might expect from an object whose defining property is that nothing can escape from it, the region surrounding a black hole is expected to be a *source* of energy. Of course, once the hot matter falls below the event horizon, its radiation is no longer detectable—it can never leave the hole.



▲ **FIGURE 13.20 Black Hole Heating** Any matter falling into the clutches of a black hole will become severely distorted and heated. This sketch shows an imaginary planet being pulled apart by a black hole's gravitational tides.

Approaching the Event Horizon

One safe way to study a black hole would be to go into orbit around it, safely beyond the disruptive influence of the hole's strong tidal forces. After all, Earth and the other planets of our solar system all orbit the Sun without falling into it and being torn apart. The gravity field around a black hole is basically no different. Let's imagine sending a less fragile (and more expendable) observer—a robot probe—toward the center of the hole, as illustrated in Figure 13.21. If our robot is small enough (to minimize the tidal force) and of sufficiently strong construction, it might conceivably survive to reach the event horizon, even if a human could not. Watching from a safe distance in our orbiting spacecraft, we can then examine the nature of space and time, at least down to the event horizon. After that boundary is crossed, there is no way for the probe to return any information about its findings.

Suppose our robot has an accurate clock and a light source of known frequency mounted on it. From our safe vantage point far outside the event horizon, we could use telescopes to read the clock and measure the frequency of the light we receive. What might we discover? We would find that the light from the robot would become more and more redshifted—shifted toward longer wavelengths—as the robot neared the event horizon (Figure 13.22). Even if the robot used rocket engines to remain motionless, the redshift would still be detected. The redshift is not caused by motion of the light source—it is not the result of the Doppler effect. *(Sec. 2.7)* Rather, it is a result of the black hole's gravitational field, clearly predicted by Einstein's general theory of relativity and known as **gravitational redshift.**

We can explain the gravitational redshift as follows. Photons are attracted by gravity. As a result, in order to escape from a source of gravity, photons must expend some energy—they have to work to get out of the gravitational field. They don't slow down (photons always move at the speed of light); they just lose energy. Because a photon's energy is proportional to the frequency of its radiation, light that loses energy must have its frequency reduced (or, conversely, its wavelength increased).

As photons traveled from the robot's light source to our orbiting spacecraft, they would become gravitationally redshifted. From our standpoint, a yellow light would appear orange, then red as the robot astronaut approached the black hole. As the robot neared the event horizon, the light would become undetectable with an optical telescope. First infrared and then radio telescopes would be needed to detect it. Theoretically, light emitted *from the event horizon itself* would be gravitationally redshifted to infinitely long wavelengths.

What about the robot's clock? What time does it tell? Is there any observable change in the rate at which the clock ticks while moving deeper into the hole's gravitational field? We would find, from our orbiting spacecraft, that any clock close to the hole would appear to tick more *slowly* than an equivalent clock on board our ship. The closer the clock came to the hole, the slower it would appear to run. Upon reaching the event horizon, the clock would seem to stop altogether. All action would become frozen in time. Consequently, we would never actually witness the robot cross the event horizon. The process would appear to take forever.

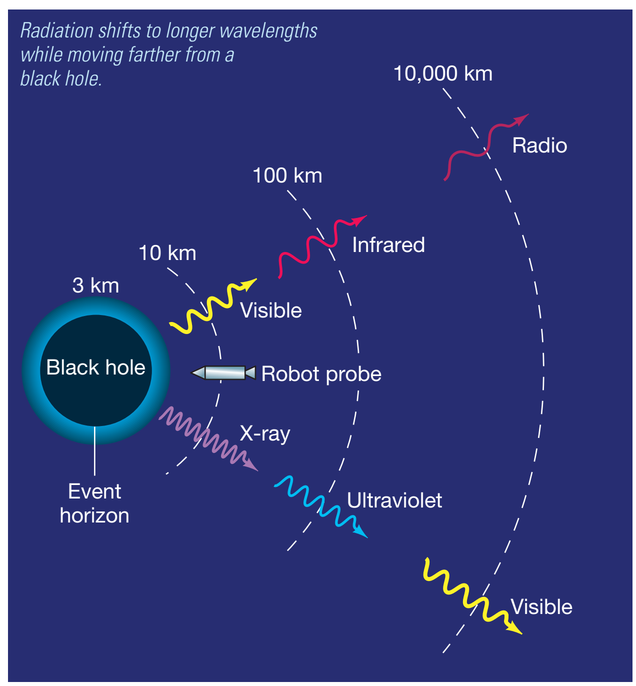
This apparent slowing down of the robot's clock is known as **time dilation** and is closely related to gravitational redshift. To see why this is so, think of the robot's light source as a clock, with the passage of a wave crest (say) constituting a "tick," so the clock ticks at the frequency of the radiation. As the wave is redshifted, the frequency drops, and fewer wave crests pass us each second—the clock appears to slow down. This thought experiment demonstrates that the redshift of the radiation and the slowing of the clock are one and the same thing.

From the point of view of the robot, relativity theory predicts no strange effects at all. The light source hasn't reddened and the clock keeps perfect time. In the robot's frame of reference, everything is normal. Nothing prohibits it from approaching within the Schwarzschild radius of the hole (so long as the probe is strong enough to avoid being torn apart by tidal forces)—no law of physics constrains an object from passing through an event horizon. There is no barrier at the event horizon and no sudden lurch as it is crossed. It is just a boundary in space, but one that can be crossed in only one direction.

Perhaps counterintuitively, the tidal force at the event horizon is *smaller* for more massive black holes (see problems 8 and 9 at the end of this chapter). Although, as we saw, an intrepid explorer would be shredded long before reaching the event horizon of a 1-solar-mass black hole, travelers passing through the event horizon of a multimillion solar mass hole (such as might lurk in the heart of our own Galaxy, as we will see in the next chapter) might not feel any particular discomfort. They would remain able to contemplate their surroundings—and the all-important fact that they couldn't reverse course—for a few more seconds before the rapidly rising tidal forces in the black hole's interior finally finished them off.

▲ **FIGURE 13.21 Robot Astronaut** A hypothetical spacecraft launches a robotic probe that travels toward a black hole to perform experiments that humans, farther away in the craft, could monitor to learn about the nature of space near the event horizon.

MA INTERACTIVE
Gravitational Time Dilation and Redshift



▶ **FIGURE 13.22 Gravitational Redshift** Photons escaping from the strong gravitational field close to a black hole must expend energy to overcome the hole's gravity. As a result, the photons change wavelength; their color changes, and their frequency lessens. This figure shows the effect on two beams of radiation, one of visible light and one of X-rays, emitted from a space probe as it nears the event horizon of a 1-solar-mass black hole.

Deep Down Inside

No doubt, you are wondering what lies within the event horizon of a black hole. The answer is simple: No one knows. However, the question raises some very fundamental issues that lie at the forefront of modern physics.

General relativity predicts that without some agent to compete with gravity, the core remnant of a high-mass star will collapse all the way to a point at which both its density and its gravitational field become infinite—a so-called **singularity.** The same applies to any infalling matter. However, we should not take this prediction of infinite density too literally. Singularities always signal the breakdown of the theory producing them. The present laws of physics are simply inadequate to describe the final moments of a star's collapse.

As it stands today, the theory of gravity is incomplete because it does not incorporate a proper description of matter on very small scales. As our collapsing stellar core shrinks to smaller and smaller radii, we eventually lose our ability even to describe, let alone predict, its behavior. Perhaps matter trapped in a black hole never actually reaches a singularity. Perhaps it just approaches this bizarre state in a manner that we will someday understand as the subject of *quantum gravity*—the merger of general relativity (the theory of the universe on the largest scales) with quantum mechanics (the theory of matter on atomic and subatomic scales)—develops.

Having said that, we can at least estimate how small the core can get before current theory fails. It turns out that by the time that stage is reached, the core is already much smaller than any elementary particle. Thus, although a complete description of the end point of stellar collapse may well require a major overhaul of the laws of physics, for all practical purposes the prediction of collapse to a point is valid. Even if a new theory somehow succeeds in doing away with the central singularity, it is very unlikely that the external appearance of the hole, or the existence of its event horizon, will change. Any modifications to general relativity are expected to occur only on submicroscopic scales, not on the macroscopic (kilometer-sized) scale of the Schwarzschild radius.

CONCEPT CHECK

Why would you never actually witness an infalling object crossing the event horizon of a black hole?

Singularities are places where the rules break down, and some very strange things may occur near them. Many possibilities have been suggested—gateways to other universes, time travel, or the creation of new states of matter, for instance—but none has been proved, and certainly none has been observed. Because these regions are places where science fails, their presence causes serious problems for many of our cherished laws of physics, including causality (the idea that cause should precede effect, which runs into immediate problems if time travel is possible) and energy conservation (which is violated if material can hop from one universe to another through a black hole). It is unclear whether the removal of the singularity by some future, all-encompassing theory would necessarily also eliminate all of these problematic side effects.

ANIMATION/VIDEO
X-Ray Binary Star

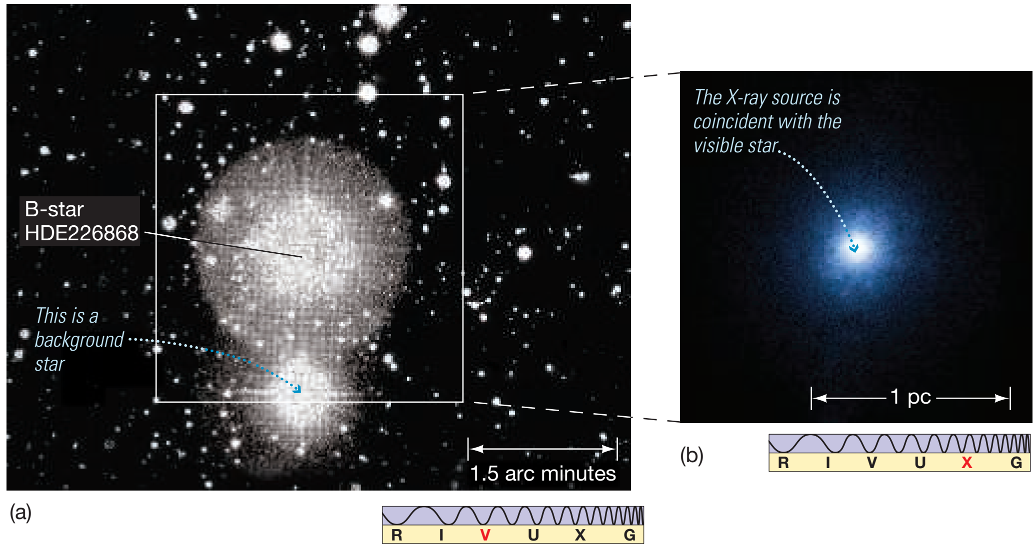
13.8 Observational Evidence for Black Holes

Theoretical ideas aside, is there any observational evidence for black holes? What proof do we have that these strange invisible objects really do exist?

Black Holes in Binary Systems

Perhaps the most promising way to find black holes is to look for their effects on other astronomical objects. Our Galaxy harbors many binary star systems in which only one object can be seen, but we need observe the motion of only one star to infer the existence of an unseen companion and measure some of its properties. ∞ *(Sec. 10.7)* In the majority of cases, the invisible companion is simply small and dim, nothing more than an M-type star hidden in the glare of an O- or B-type partner, or perhaps shrouded by dust or other debris, making it invisible to even the best available equipment. In either case, the invisible object is not a black hole.

A few close binary systems, however, have peculiarities suggesting that one of their members may be a black hole. Figure 13.23(a) shows the area of the sky in the constellation Cygnus, where the evidence is particularly strong. The system of interest lies some 2000 pc from Earth. The black hole candidate is an X-ray source called Cygnus X-1, discovered in the early 1970s. Its visible companion is a blue B-type giant. Assuming that it lies on the main sequence, its mass must be around 25 times the mass of the Sun. Spectroscopic observations indicate that the binary system has an orbital period of 5.6 days. Combining this information with spectroscopic measurements of the visible component's orbital speed, astronomers estimate the total mass of the binary system to be around 35 solar masses, implying that Cygnus X-1 has a mass of about 10 times that of the Sun.



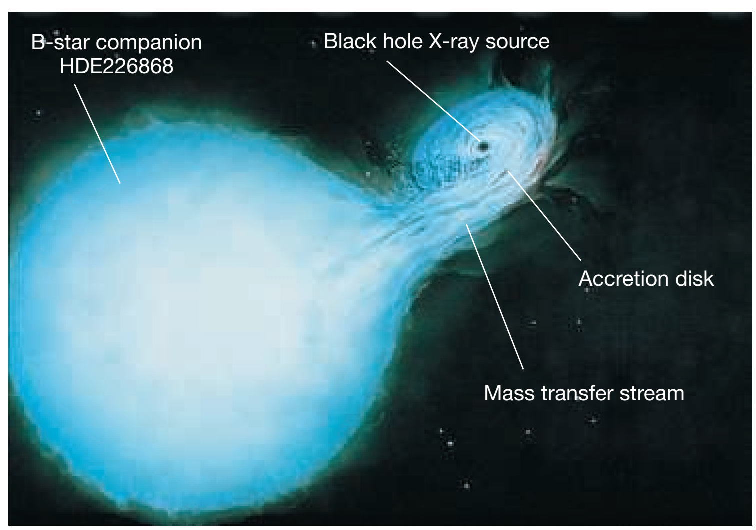
▲ **FIGURE 13.23 Cygnus X-1** (a) The brightest star in this photograph (called HDE226868) is a member of a binary system whose unseen companion, called Cygnus X-1, is a leading black hole candidate. The system lies approximately 2000 pc away. (b) A *Chandra* X-ray image of the field of view outlined by the square in part (a). The X-rays are not coming from the star. Rather, they come from the black hole companion, which orbits so close to the star that their roughly 0.1 AU separation cannot be seen on this (roughly 1 pc) scale. Neither the star nor Cygnus X-1 are nearly as large as these images suggest. Both are so bright that their light spills over into the surrounding image. *(Harvard-Smithsonian Center for Astrophysics; CXO)*

X-ray radiation emitted from the immediate neighborhood of Cygnus X-1 indicates the presence of high-temperature gas, perhaps as hot as several million kelvins. Furthermore, the X-ray emission has been observed to vary in intensity on time scales as short as a millisecond. As discussed earlier in the context of gamma-ray bursts, for this variation not to be blurred by the travel time of light across the source, Cygnus X-1 cannot be more than 1 light-millisecond, or 300 km, in diameter.

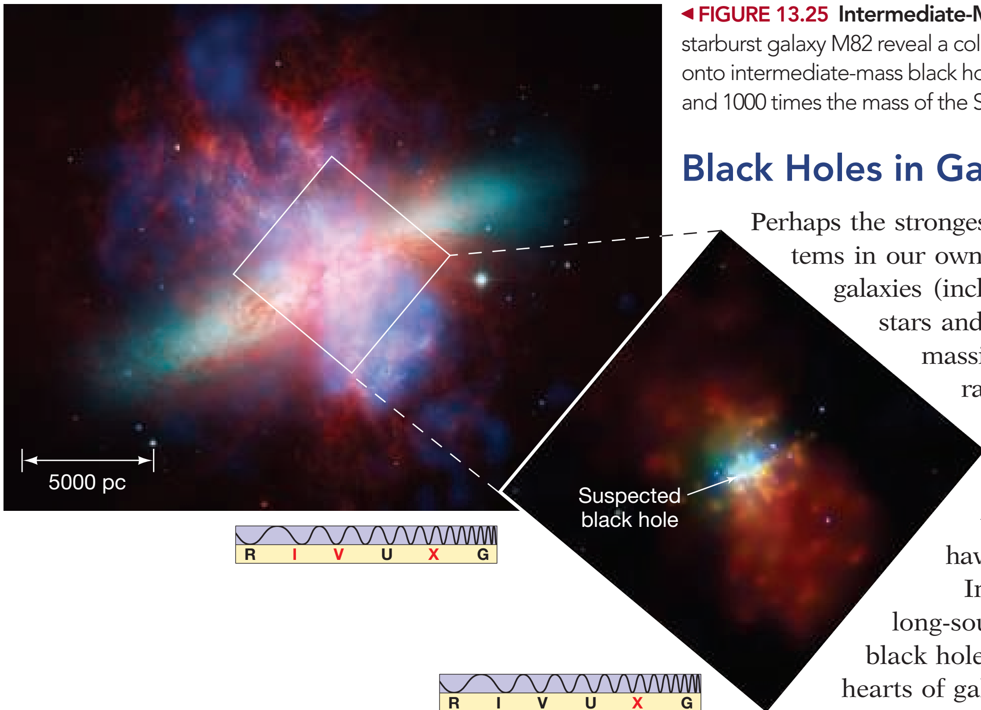
These properties suggest that Cygnus X-1 could be a black hole. Figure 13.24 is an artist's conception of this intriguing object. The X-ray-emitting region is likely an accretion disk formed as matter drawn from the visible star spirals down onto the unseen component. The rapid variability of the X-ray emission indicates that the unseen component must be very compact—a neutron star or a black hole. Its large mass, well above the neutron star mass limit discussed earlier, implies the latter.

MA ANIMATION / VIDEO
Black Hole and Companion Star

A few other black hole candidates are known. For example, LMC X-3—the third X-ray source ever discovered in the Large Magellanic Cloud, a small galaxy orbiting our own (see Section 15.2)—is an invisible object that, like Cygnus X-1, orbits a bright companion star. LMC X-3's visible companion seems to be distorted into the shape of an egg by the unseen object's intense gravitational pull. Reasoning similar to that applied to Cygnus X-1 leads to the conclusion that LMC X-3 has a mass nearly 10 times that of the Sun, making it too massive to be anything but a black hole. The X-ray binary system A0620-00 has been found to contain an invisible compact object of mass 3.8 times the mass of the Sun. In total, about 20 known objects may turn out to be black holes; Cygnus X-1, LMC X-3, and A0620-00 probably have the strongest claims.



▶ **FIGURE 13.24 Black Hole** INTERACTIVE Artist's conception of a binary system containing a large, bright, visible star and an invisible, X-ray-emitting black hole. (Compare Figure 12.14). This painting is based on data obtained from many observations of Cygnus X-1. *(L. Chaisson)*



◀ **FIGURE 13.25 Intermediate-Mass Black Holes?** X-ray observations (inset) of the center of the starburst galaxy M82 reveal a collection of bright sources that may be the result of matter accreting onto intermediate-mass black holes. The black holes are probably young, have masses between 100 and 1000 times the mass of the Sun, and lie relatively far from the center of M82. *(Subaru; NASA)*

Black Holes in Galaxies

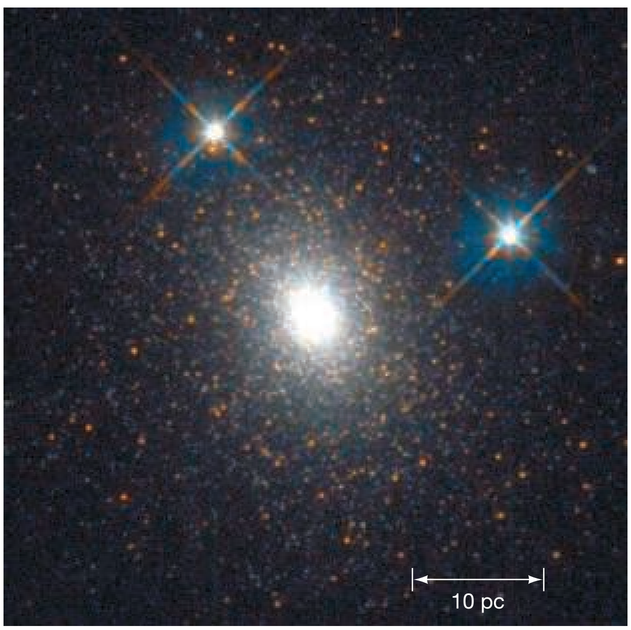
Perhaps the strongest evidence for black holes comes not from binary systems in our own Galaxy but from observations of the centers of many galaxies (including our own), where astronomers have found that stars and gas are moving extremely rapidly, orbiting some very massive, unseen object. Masses inferred from Newton's laws range from millions to billions of times the mass of the Sun. ∞ *(More Precisely 1-1)* The leading (and at present, the only) explanation is that these objects are black holes. We will return to these observations, and the question of how such *supermassive black holes* might have formed, in the next three chapters.

In 2000, X-ray astronomers reported evidence for a long-sought but elusive missing link between "stellar-mass" black holes in binaries and the supermassive black holes in the hearts of galaxies. Figure 13.25 shows an unusual looking galaxy called M82, currently the site of an intense and widespread burst of star formation (see Chapter 15). The inset shows a *Chandra* image of the innermost few thousand parsecs of M82, revealing a number of bright X-ray sources close to—but *not* at—the center of the galaxy. Their spectra and X-ray luminosities suggest that they may be accreting compact objects with masses ranging from 100 to almost 1000 times the mass of the Sun. If confirmed, they will be the first *intermediate-mass black holes* ever observed.

Too large to be remnants of normal stars and too small to warrant the "supermassive" label, these objects present a puzzle to astronomers. One possible origin is suggested by an apparent association between some of the X-ray emitters in M82 and elsewhere and dense, young star clusters. Theorists speculate that collisions between high-mass stars in the congested cores of these clusters might lead to the runaway growth of an extremely massive and very unstable star, which then collapses to form an intermediate-mass black hole. However, both the observations and this explanation remain controversial. Figure 13.26 shows the current best candidate for a "nearby" star cluster harboring an intermediate-mass black hole—the globular cluster G1 in the Andromeda galaxy. ∞ *(Sec. 2.1)* The peculiar orbits of stars near the center of this cluster suggest a black hole of mass 20,000 times that of the Sun, and observations of the cluster in both radio and X-rays are consistent with theoretical expectations of the emission from such a massive object in the cluster's core.

ANIMATION/VIDEO
Black Hole in Galaxy M87 MA

ANIMATION/VIDEO
Supermassive Black Hole MA



▲ **FIGURE 13.26 Black Hole Host?** The star cluster G1 is the most massive globular cluster in the Andromeda galaxy, but the stars near its center do not move as expected if the cluster's mass is as smoothly distributed as its light. Instead, the observations suggest that an intermediate-mass black hole resides at the cluster's center. *(NASA)*

CONCEPT CHECK

How do astronomers "see" black holes?

THE BIG QUESTION

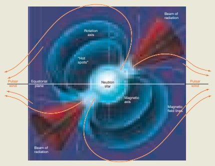
Are black holes for real? Decades ago, many astronomers regarded black holes as a kind of cosmic cop-out—the last resort of researchers who couldn't decipher the bizarre phenomena they observed. But now, improved observations really do point toward stellar remnants that are denser, brighter, and much more puzzling than the already peculiar neutron stars. We have to conclude that, strange as they are, black holes have been detected in our Galaxy and beyond. Perhaps someday future generations of space travelers will visit Cygnus X-1 or the center of our Galaxy and (carefully!) test these conclusions firsthand. Still, might there be other weird collapsed remnants—quark stars, perhaps—that stop short of being genuine black holes?

CHAPTER REVIEW

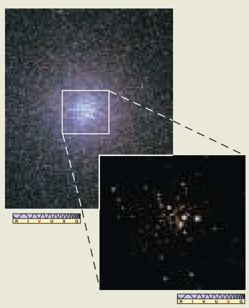
SUMMARY

LO1 A core-collapse supernova may leave behind an ultracompressed ball of material called a **neutron star** (p. 362). This is the remnant of the inner core that rebounded and blew the rest of the star apart. Neutron stars are extremely dense and, at formation, are predicted to be extremely hot, strongly magnetized, and rapidly rotating. They cool down, lose much of their magnetism, and slow down as they age.

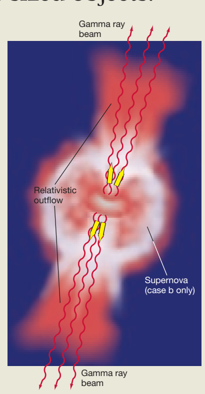
LO2 According to the **lighthouse model** (p. 364), neutron stars, because they are magnetized and rotating, send regular bursts of electromagnetic energy into space. The beams are produced by charged particles confined by the strong magnetic fields. When we can see the beams from Earth, we call the source neutron star a **pulsar** (p. 362). The pulse period is the rotation period of the neutron star.



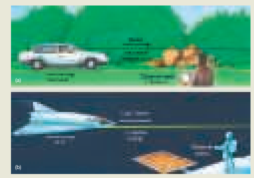
LO3 A neutron star that is a member of a binary system can draw matter from its companion, forming an accretion disk, which is usually a strong source of X-rays. As gas builds up on the star's surface, it eventually becomes hot enough to fuse hydrogen. When hydrogen burning starts on a neutron star, it does so explosively, and an **X-ray burster** (p. 366) results. The rapid rotation of the inner part of the accretion disk causes the neutron star to spin faster as new gas arrives on its surface. The eventual result is a very rapidly rotating neutron star—a **millisecond pulsar** (p. 366). Many millisecond pulsars are found in the hearts of old globular clusters. They cannot have formed recently, and must have been spun up by interactions with other stars. Careful analysis of the radiation received has shown that some millisecond pulsars are orbited by planet-sized objects.



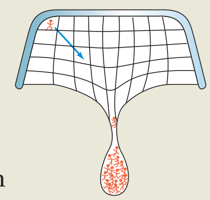
LO4 **Gamma-ray bursts** (p. 368) are very energetic flashes of gamma rays that occur about once a day and are distributed uniformly over the entire sky. In some cases, their distances have been measured, placing them at very large distances and implying that they are extremely luminous. The leading theoretical models for these explosions involve the violent merger of neutron stars in a distant binary system, or the recollapse and subsequent violent explosion following a "failed" supernova in a very massive star.



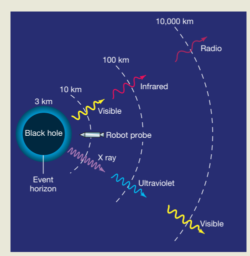
LO5 Einstein's special theory of relativity deals with the behavior of particles moving at speeds comparable to the speed of light. It agrees with Newton's theory at low velocities, but makes many very different predictions for high-speed motion. All of its predictions have been repeatedly verified by experiment. The modern replacement for Newtonian gravity is Einstein's **general theory of relativity** (p. 373), which describes gravity in terms of the warping, or bending, of space by the presence of mass. The more mass, the greater the warping. All particles—including photons—respond to that warping by moving along curved paths.



LO6 The upper limit on the mass of a neutron star is about three solar masses. Beyond that mass, the star can no longer support itself against its own gravity, and it collapses to form a **black hole** (p. 373), a region of space from which nothing can escape. The most massive stars, after exploding in a supernova, form black holes rather than neutron stars. Conditions in and near black holes can only be described by general relativity. The radius at which the escape speed from a collapsing star equals the speed of light is called the **Schwarzschild radius** (p. 374). The surface of an imaginary sphere centered on the collapsing star and having a radius equal to the star's Schwarzschild radius is called the **event horizon** (p. 374).

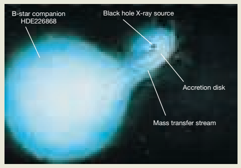


LO7 To a distant observer, light leaving a spaceship that is falling into a black hole would be subject to **gravitational redshift** (p. 381) as the light climbed out of the hole's intense gravitational field. At the same time, a clock on the spaceship would show **time dilation** (p. 381)—the clock would appear to slow down as the ship approached the event horizon. The observer would never see the ship reach the surface of the hole. Once within the event horizon, no known force can prevent a collapsing star from contracting all



the way to a pointlike **singularity** (p. 382), at which point both the density and the gravitational field of the star become infinite. This prediction of relativity theory has yet to be proved. Singularities are places where the known laws of physics break down.

LO8 Once matter falls into a black hole, it can no longer communicate with the outside. However, on its way in, it can form an accretion disk and emit X-rays.



The best place to look for a black hole is in a binary system in which one component is a compact X-ray source. Cygnus X-1, a well-studied X-ray source in the constellation Cygnus, is a long-standing black-hole candidate. Studies of orbital motions imply that some binaries contain compact objects too massive to be neutron stars, leaving black holes as the only alternative. There is also substantial evidence for more massive black holes residing in or near the centers of many galaxies, including our own.

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Problems labeled **POS** explore the process of science. **VIS** problems focus on reading and interpreting visual information. **LO** connects to the introduction's numbered Learning Outcomes.

REVIEW AND DISCUSSION

1. **LO1** How does the way in which a neutron star forms determine some of its most basic properties?
2. What would happen to a person standing on the surface of a neutron star?
3. **LO2** Why aren't all neutron stars seen as pulsars?
4. What are X-ray bursters?
5. **LO3** What is the favored explanation for the rapid spin rates of millisecond pulsars?
6. Why do you think astronomers were surprised to find a pulsar with a planetary system?
7. Why do astronomers think there are two basically different types of gamma-ray burst?
8. What does it mean to say that the measured speed of a light beam is independent of the motion of the observer?
9. **LO6** Use your knowledge of escape speed to explain why black holes are said to be "black."
10. What is an event horizon?
11. **LO5** **POS** Why is it so difficult to test the predictions of the theory of general relativity? Describe two tests of the theory.
12. **LO7** What would happen to someone falling into a black hole?
13. **LO8** **POS** What makes Cygnus X-1 a good black hole candidate?
14. **POS** Imagine that you had the ability to travel at will through the Milky Way Galaxy. Explain why you would discover many more neutron stars than those known to observers on Earth. Where would you be most likely to find these objects?
15. **POS** Do you think that planet-sized objects discovered in orbit around a pulsar should be called planets? Why or why not?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. Newly formed neutron stars have extremely strong magnetic fields. (T/F)
2. All millisecond pulsars are now, or once were, members of binary star systems. (T/F)
3. The fact that gamma-ray bursts are so distant means that they must be very energetic events. (T/F)
4. All things, except light, are attracted by gravity. (T/F)
5. According to general relativity, space is warped, or curved, by matter. (T/F)
6. Although visible light cannot escape from a black hole, high-energy radiation, like gamma rays, can. (T/F)
7. Thousands of black holes have now been identified in our Galaxy. (T/F)
8. A neutron star is about the same size as (a) a school bus; (b) a U.S. city; (c) the Moon; (d) Earth.
9. The most rapidly "blinking" pulsars are those that (a) spin fastest; (b) are oldest; (c) are most massive; (d) are hottest.
10. The X-ray emission from a neutron star in a binary system comes mainly from (a) the hot surface of the neutron star itself; (b) heated material in an accretion disk around the neutron star; (c) the neutron star's magnetic field; (d) the surface of the companion star.
11. Gamma-ray bursts are observed to occur (a) mainly near the Sun; (b) throughout the Milky Way Galaxy; (c) approximately uniformly over the entire sky; (d) near pulsars.
12. If the Sun were magically to turn into a black hole of the same mass, (a) Earth would start to spiral inward; (b) Earth's orbit would remain unchanged; (c)Earth would fly off into space; (d) Earth would be torn apart by the black hole's gravity.
13. The best place to search for black holes is in a region of space that(a) is dark and empty; (b) has recently lost some stars; (c) has strong X-ray emission; (d) is cooler than its surroundings.
14. **VIS** According to Figure 13.3 (Pulsar Model), the beam of a pulsar is emitted (a) along the rotation axis; (b) in the equatorial plane; (c) from the magnetic poles; (d) in a single direction in space.
15. **VIS** Figure 13.10 (Gamma-Ray Bursts) shows that gamma-ray bursts (a) are all very similar; (b) sometimes last for less than a second; (c) are confined to the Galactic plane; (d) come from great distances.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ The angular momentum of a spherical body is proportional to the body's angular speed times the square of its radius. ∞ *(More Precisely 4-1)* Using the law of conservation of angular momentum, estimate how fast a collapsed stellar core would spin if its initial spin rate was one revolution per day and its radius decreased from 10,000 km to 10 km.
2. ■ What would your mass be if you were composed entirely of neutron star material of density 3×10^{10} (Assume that your average density is 1000 kg/m^2.) Compare this with the mass of (a) the Moon; (b) a typical 1-km diameter asteroid.
3. ■ Calculate the surface gravity (relative to Earth's gravity of) and the escape speed of a 1.4-solar-mass neutron star with a radius of 10 km. What would be the escape speed of a 1-solar-mass object with a radius of 3 km? ∞ *(More Precisely 5-1)*
4. ■■ Use the radius–luminosity–temperature relation to calculate the luminosity of a 10-km-radius neutron star for temperatures of 10^5 K, 10^7 K and 10^9 K. What do you conclude about the visibility of neutron stars? Could the coolest of them be plotted on our H–R diagram?
5. ■■ A gamma-ray detector of area 0.5 m^2 observing a gamma-ray burst records photons having total energy 10^{-8} joules. If the burst occurred 1000 Mpc away, calculate the total amount of energy it released (assuming that the energy was emitted equally in all directions). How would this figure change if the burst occurred 10,000 pc away instead, in the halo of our Galaxy? What if it occurred within the Oort cloud of our own solar system, at a distance of 50,000 AU?
6. ■■ An unstable elementary particle is known to decay into other particles in 2 μs, as measured in a laboratory where the particle is at rest. A beam of such particles is accelerated to a speed of 99.99 percent of the speed of light. How long do the particles in the beam take to decay, in the laboratory frame of reference?
7. ■ Supermassive black holes are thought to exist in the centers of some galaxies. What would be the Schwarzschild radii of black holes of 1 million and 1 billion solar masses? How does the first black hole compare in size with the Sun? How does the second compare in size with the solar system?
8. ■■ Calculate the tidal acceleration on a 2-m-tall human falling feet first into a 1-solar-mass black hole—that is, compute the difference in the accelerations (forces per unit mass) on his head and his feet just before his feet cross the event horizon. Repeat the calculation for a 1-million-solar-mass black hole and for a 1-billion-solar-mass black hole (see the previous question). Compare these accelerations with the acceleration due to gravity on Earth.
9. ■■■ Endurance tests suggest that the human body cannot withstand stress greater than about 10 times the acceleration due to gravity on Earth's surface. At what distance from a 1-solar-mass black hole would the human in the previous question be torn apart? Calculate the minimum mass of a black hole for which an infalling human could just reach the event horizon intact.
10. ■■ Using the data given in the text (assume the upper limit on the stated range for the black hole mass), calculate the orbital separation of Cygnus X-1 and its B-type stellar companion. ∞ *(Sec. 1.4)*

ACTIVITIES

Collaborative

1. We can't easily observe a black hole, or make one to study, but theorists have lots to say about their properties! The text focuses on the simplest possible type of black hole—the uncharged, nonrotating *Schwarzchild* black hole—but there is a large body of literature on charged and spinning black holes, too. Charged black holes don't figure much in astronomy—the universe is electrically neutral on macroscopic scales—but rotating *Kerr* black holes are in fact very important. Divide your group in two and research online the properties of Schwarzchild and Kerr black holes. You'll probably find more information on the simpler Schwarzchild case, but some persistence will yield a lot on the rotating Kerr case, too. Combine your research to make a joint presentation on the similarities and differences between the two types. Focus on properties such as the event horizon, the singularity, and the orbits of light and matter near the hole. How fast can a black hole rotate? Which kind of black hole is thought to be most common in nature?

Individual

1. Find the ninth-magnitude companion to Cygnus X-1, the sky's most famous black hole candidate. Because none of us can see X-rays, no sign of anything unusual can be seen. Still, it's fun to gaze toward this region of the heavens and contemplate Cygnus X-1's powerful energy emission and strange properties. Even without a telescope, it is easy to locate the region of the heavens where Cygnus X-1 resides. The constellation Cygnus contains a recognizable star pattern called the Northern Cross. The star in the center of the crossbar is called Sadr. The star at the bottom of the cross is called Albireo. Approximately midway between Sadr and Albireo lies the star Eta Cygni. Cygnus X-1 is located slightly less than 0.5° from this star. Whether or not you are using a telescope, sketch what you see.

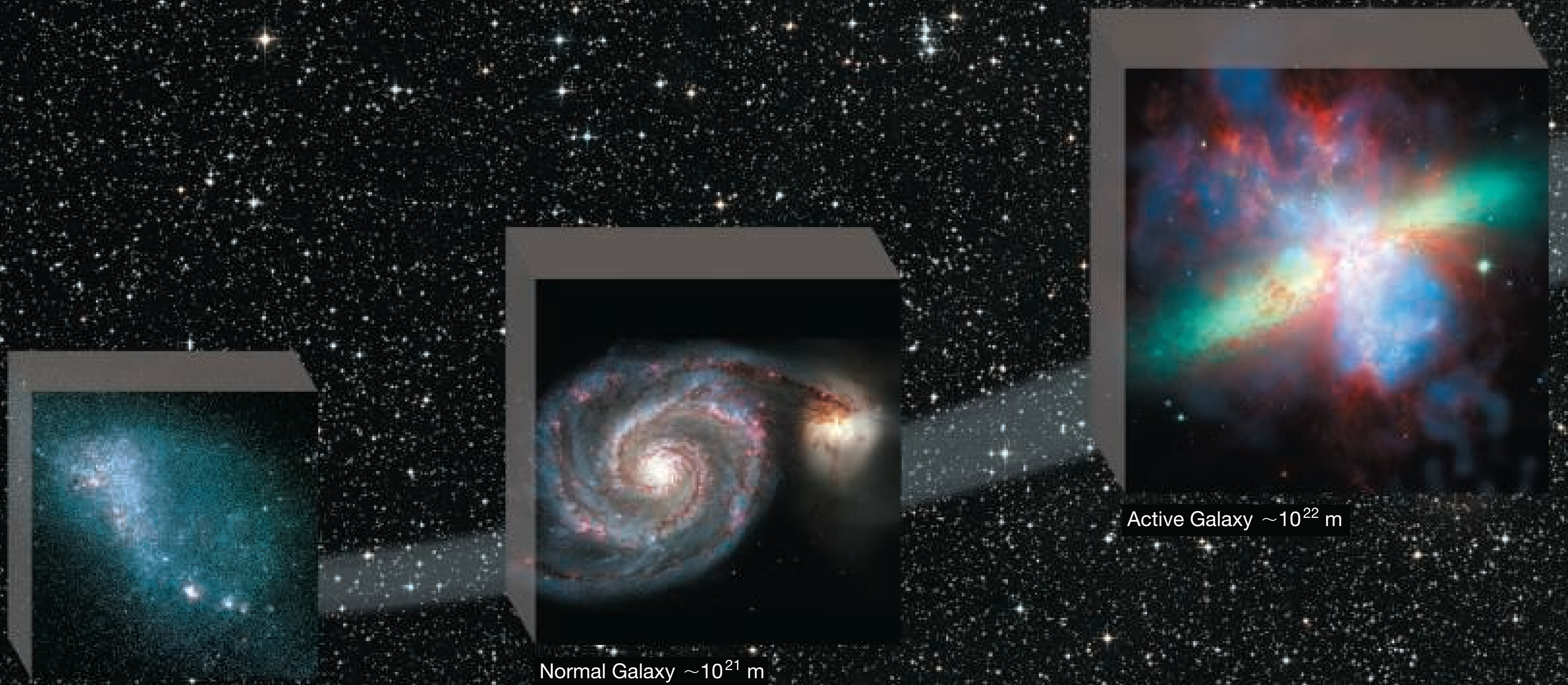
PART 4

Galaxies and the Universe

Our home Galaxy—the Milky Way—is a thousand times bigger than anything we have considered thus far in this book. Yet this vast system, more than 100,000 light-years across and home to 100 billion stars, is but one of billions of galaxies strewn across the vast expanse of deep space.

Part 4 explores the properties of galaxies, the glorious "building blocks" of the universe. Collectively they, trace out truly gargantuan patterns that top the hierarchy of material structures in the cosmos. On these huge scales, we enter the realm of fundamental inquiry that has preoccupied philosophers since the dawn of recorded time: How did our universe begin? And how will it end?

The images here illustrate cosmic objects in Part 4, all of them at least a million million million times beyond any familiar terrestrial scale.



Dwarf Galaxy $\sim 10^{20}$ m

Normal Galaxy $\sim 10^{21}$ m

Active Galaxy $\sim 10^{22}$ m

A single galaxy has more stars in it than the number of people who have ever lived on Earth.

14

The Milky Way Galaxy

A Spiral in Space

Looking up on a dark, clear night, we are struck by two aspects of the night sky. The first is that the individual stars we see are roughly uniformly distributed in all directions. They all lie relatively close to us, mapping out the local galactic neighborhood within a few hundred parsecs of the Sun. But this is only a local impression. Ours is a rather provincial view. Beyond those nearby stars, the second thing we notice is a fuzzy band of light—the Milky Way—stretching across the heavens. From the Northern Hemisphere, this band is most easily visible in the summertime, arcing high above the horizon. Its full extent forms a great circle that encompasses the entire celestial sphere. This is the insider's view of the galaxy in which we live, the blended light of countless distant stars. As we consider much larger volumes of space, on scales far, far greater than the distances between neighboring stars, a new level of organization becomes apparent as the large-scale structure of the Milky Way Galaxy is revealed.

THE BIG PICTURE

Our Milky Way Galaxy is just one among nearly a hundred billion other galaxies in the observable universe—a hundred billion galaxies! For astronomers, the Milky Way plays much the role for galaxies as the Sun does for stars. Our understanding of galaxies throughout the cosmos rests squarely on our knowledge of the size, scale, structure, composition, and dynamics of our own Galactic home.

◀ Stars cluster into gigantic assemblages called galaxies, of which our Milky Way Galaxy is just one among roughly a hundred billion others. Galaxies such as this one, known as M74 and shown here in true color, in turn contain roughly a hundred billion stars. As we now enter the realm of very big dimensions, the graceful winding arms of this majestic spiral galaxy resemble a curving staircase sweeping across some 100,000 light-years of space. Its size, shape, and mass approximate those of our Galaxy, which has never been photographed in its full grandeur because we live inside it. If this were our Galaxy, the Sun would reside in one of its spiral arms, about two-thirds of the way out from the center. *(NASA)*

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Describe the overall structure of the Milky Way Galaxy, and say how the various regions differ from one another.
- **LO2** Explain the importance of variable stars in determining the size and shape of our Galaxy.
- **LO3** Compare and contrast the orbital motions of stars in different regions of the Galaxy.
- **LO4** Interpret the differences between disk and halo stars in terms of our current understanding of how our Galaxy formed.
- **LO5** Present some possible explanations for the spiral arms observed in our own and many other galaxies.
- **LO6** Explain what studies of Galactic rotation reveal about the size and mass of our Galaxy, and discuss the possible nature of dark matter.
- **LO7** Describe the evidence for a supermassive black hole at the center of our Galaxy.

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14.1 Our Parent Galaxy

A **galaxy** is a gargantuan collection of stellar and interstellar matter—stars, gas, dust, neutron stars, black holes—isolated in space and held together by its own gravity. Astronomers are aware of literally billions of galaxies beyond our own. The particular galaxy we happen to inhabit is known as the **Milky Way Galaxy,** or just "the Galaxy," with a capital "G."

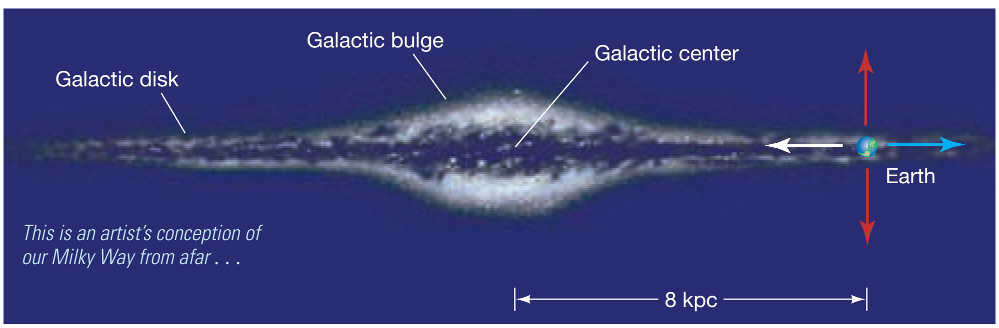
Our Sun lies in a part of the Galaxy known as the **Galactic disk,** an immense, circular, flattened region containing most of our Galaxy's luminous stars and interstellar matter (and almost everything we have studied so far in this book). Figure 14.1 illustrates how, viewed from within, the Galactic disk appears as a band of light—the *Milky Way*—stretching across our nighttime sky. Seen from Earth, the center of the disk (indeed, of the entire Galaxy) lies in the direction of the constellation Sagittarius. As indicated in the figure, if we look in a direction away from the Galactic disk (red arrows), relatively few stars lie in our field of view. However, if our line of sight happens to lie within the disk (white and blue arrows), we see so many stars that their light merges into a continuous blur.

Paradoxically, although we can study individual stars and interstellar clouds near the Sun in great detail, our location within the Galactic disk makes deciphering our Galaxy's large-scale structure from Earth a very difficult task—a little like trying to unravel the layout of paths, bushes, and trees in a city park without being able to leave one particular park bench. In many directions, the interpretation of what we see is inconclusive, with foreground objects obscuring our view of what lies beyond. As a result, astronomers who study the Milky Way Galaxy are often guided in their efforts by comparisons with more distant, but much more easily observable, galaxies. There is every reason to suppose that *all* the features of our Galaxy described in this chapter are shared by billions of other galaxies across the universe.

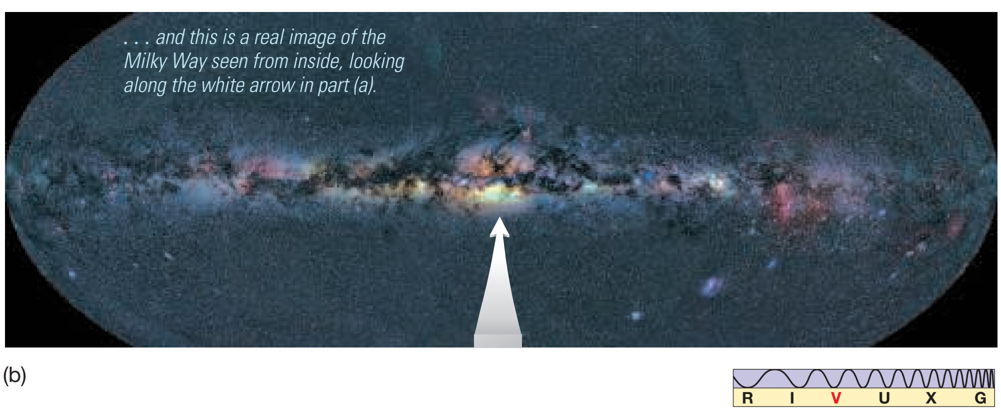
CONCEPT CHECK

Why do we see the Milky Way as a band of light across the sky?

Figure 14.2 shows three galaxies thought to resemble our own in overall structure. Figure 14.2(a) is the Andromeda Galaxy, the nearest major galaxy to the Milky Way Galaxy, lying about 800 kpc (about 2.5 million light-years) away. Andromeda's apparent elongated shape is a result of the angle at which we happen to view it. In fact, this galaxy, like our own, consists of a thin circular *galactic disk* of matter that fattens to a **galactic bulge** at the center. The disk and bulge are embedded in a roughly spherical ball of faint old stars known as the **galactic halo.** These three basic galactic regions are indicated on the figure (the halo stars are too faint to see here; see Figure 14.9 for a clearer view). Figures 14.2(b) and (c) show images of two other galaxies—one seen face-on, the other edge-on—that illustrate these points more clearly.

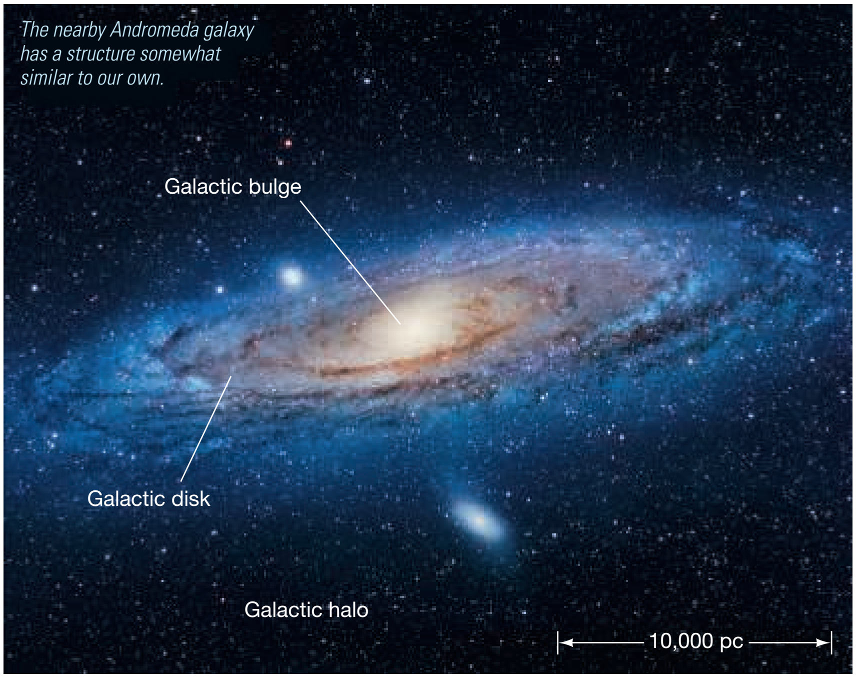


(a)



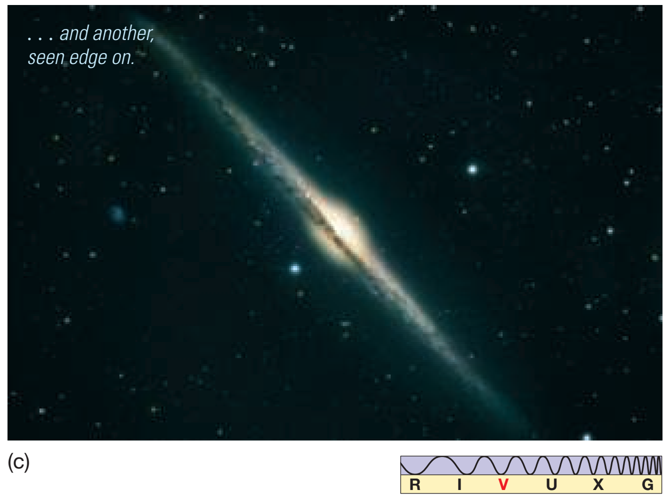
(b)

◄ **FIGURE 14.1 Galactic Plane** (a) Gazing from Earth toward the Galactic center (white arrow) in this artist's conception, we see myriad stars stacked up within the thin band of light known as the Milky Way. In the opposite direction (blue arrow), we see little of our Galaxy, much as when looking perpendicular to the disk (red arrows) where far fewer stars can be seen. (b) A real optical view of the sky in the direction of the white arrow shows the fuzzy (mostly white and "milky") band or disk of our Milky Way Galaxy (see Fig 11.1). *(Axel Mellinger)*



(a)

(b)



(c)

▲ **FIGURE 14.2 Disk Galaxies** (a) The Andromeda galaxy closely resembles the overall layout of our Milky Way Galaxy. Its disk and bulge are clearly visible in this image, which is about 30,000 pc across. (b) This galaxy, named M101 and seen nearly face-on, is similar in its overall structure to our own Milky Way Galaxy and Andromeda. (c) The galaxy NGC 4565 is oriented edge-on, allowing us to see clearly its disk and central bulge. *(R. Gendler; NASA)*

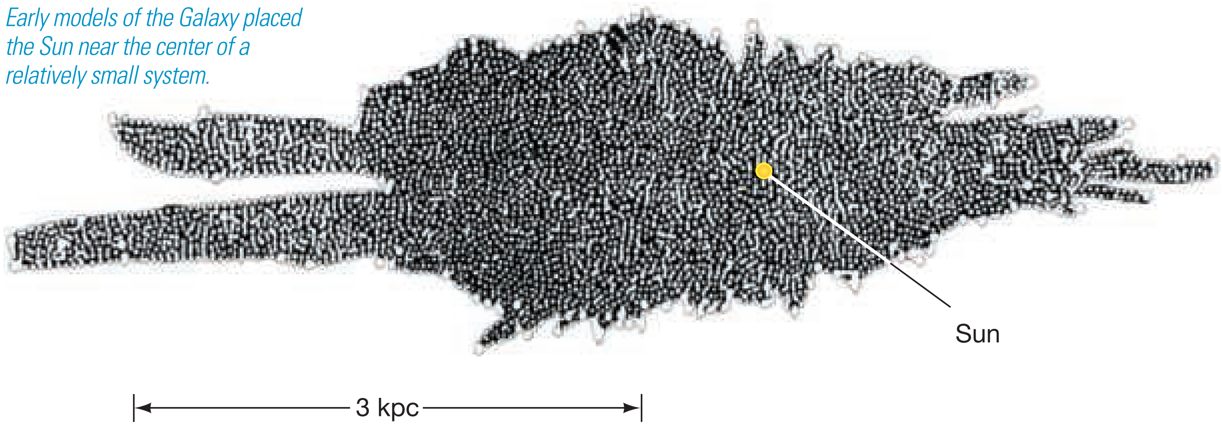
14.2 Measuring the Milky Way

Before the 20th century, astronomers' conception of the cosmos differed markedly from the modern view. The growth in our knowledge of our Galaxy, as well as the realization that there are many other distant galaxies similar to our own, has gone hand in hand with the development of the cosmic distance scale.

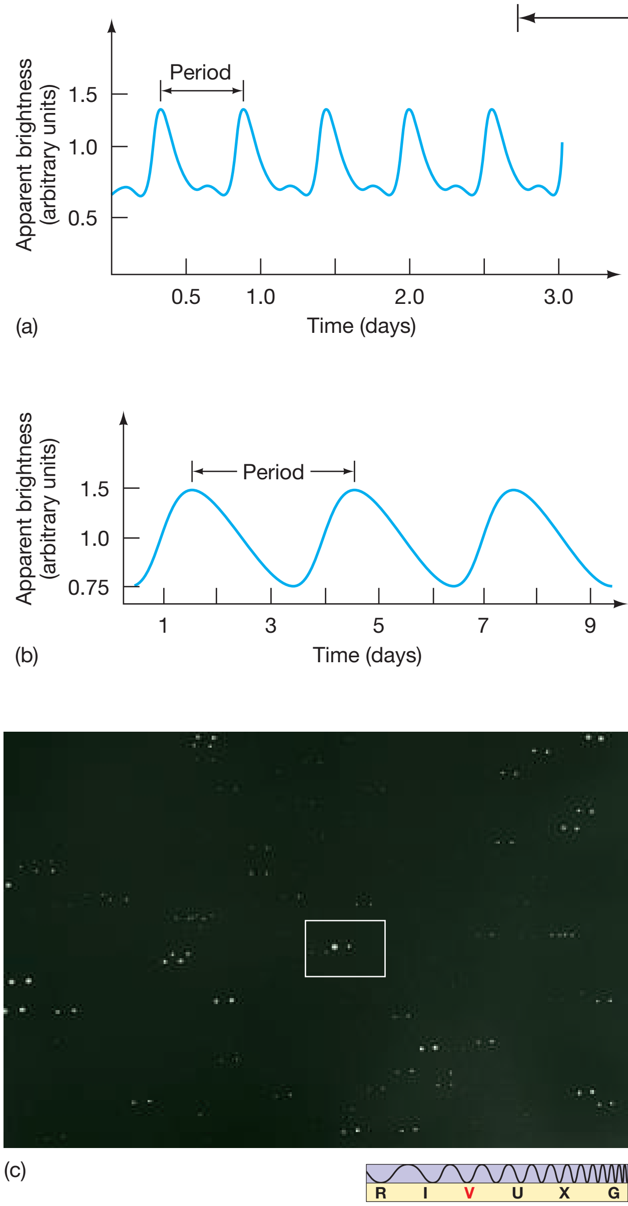
Star Counts

In the late 18th century, long before the distances to any stars were known, English astronomer William Herschel tried to estimate the shape of our Galaxy simply by counting how many stars he could see in different directions in the sky. Assuming that all stars were of about equal brightness, he concluded that the Galaxy was a somewhat flattened, roughly disk-shaped collection of stars lying in the plane of the Milky Way, with the Sun at its *center* (Figure 14.3). Subsequent refinements to this approach led to essentially the same picture. Herschel was unable to estimate the *size* of the Galaxy by this method, but early in the 20th century, with improved knowledge of the properties of stars, some researchers estimated the dimensions of this "Galaxy" as about 10 kpc in diameter by 2 kpc thick.

In fact, the Milky Way Galaxy is several tens of kiloparsecs across, and the Sun lies far from the center. The flaw in the above reasoning is that the observations were made in the visible part of the electromagnetic spectrum, and astronomers failed to take into account the absorption of visible light by the then unknown interstellar gas and dust. ∞ *(Sec. 11.1)* Only in the 1930s did



▶ **FIGURE 14.3 Herschel's Galaxy Model** Eighteenth-century English astronomer William Herschel constructed this "map" of the Galaxy by counting the number of stars he saw in different directions in the sky. Our Sun (marked by the yellow dot) appears to lie near the center of the distribution. The long axis of the diagram roughly parallels the plane of the disk.



▲ **FIGURE 14.4 Variable Stars** Light curves of (a) the pulsating variable star RR Lyrae, which has a period of less than a day, and (b) of the Cepheid variable star WW Cygni, having a period of several days. (c) This same Cepheid is shown here (boxed) on successive nights, near its maximum and minimum brightness; two photos, one from each night, were superposed and then slightly displaced. *(Harvard College Observatory)*

astronomers begin to realize the true extent and importance of the interstellar medium.

The apparent falloff in the density of stars with distance in the plane of the Milky Way is not a real thinning of their numbers in space, but simply a consequence of the murky environment in the Galactic disk. Objects in the disk lying more than a few kiloparsecs away are hidden from our view by the effects of interstellar absorption. The long "fingers" in Herschel's map are directions where the obscuration happens to be a little less severe than in others.

The falloff in density perpendicular to the disk is real. Radiation coming to us from above or below the plane of the Galaxy, where there is less gas and dust along the line of sight, arrives on Earth relatively unscathed. There is still some patchy obscuration, but the Sun happens to lie in a location where the view out of the disk is largely unimpeded by nearby interstellar clouds.

Observations of Variable Stars

An important by-product of the laborious effort to catalog stars around the turn of the 20th century was the systematic study of **variable stars.** These are stars whose luminosities change significantly over relatively short periods of time—some quite erratically, others more regularly. Only a small fraction of stars fall into this category, but those that do are of great astronomical significance.

We have encountered several examples of variable stars in earlier chapters. Often, the variability is the result of membership in a binary system. Eclipsing binaries and novae are cases in point. ∞ ***Secs 10.7 and 12.3*** However, sometimes the variability is an intrinsic property of the star itself. Particularly important to Galactic astronomy are the **pulsating variable stars,** which vary cyclically in luminosity in very characteristic ways. Note that these stars have *nothing* whatsoever to do with pulsars, which represent an entirely different stage of stellar evolution. ∞ ***Sec. 13.2*** Two types of pulsating variable stars that have played central roles in revealing both the true extent of our Galaxy and the distances to our galactic neighbors are the **RR Lyrae** and **Cepheid** variables. (Following long-standing astronomical practice, the names come from the first star of each class discovered—in this case the variable star labeled RR in the constellation Lyra and the variable star Delta Cephei, the fourth brightest star in the constellation Cepheus.)

RR Lyrae and Cepheid variable stars are recognizable by the characteristic shapes of their light curves. RR Lyrae stars all pulsate in essentially similar ways (Figure 14.4a), with only small differences in period (the time from peak to peak) from one to another. Observed periods range from about 0.5 to 1 day. Cepheid variables also pulsate in distinctive ways (the regular "sawtooth" pattern in Figure 14.4b), but different Cepheids can have very different pulsation periods, ranging from about 1 to 100 days. In either case, the stars can be recognized and identified *just by observing the variations in the light they emit*.

Pulsating variable stars are normal stars experiencing a brief (perhaps a few million years) period of instability as a natural part of stellar evolution. The conditions necessary to cause pulsations are not found in main-sequence stars. However, they do occur in post-main-sequence stars as they expand and cool on their way to becoming red giants. On the H–R diagram, these unstable stars are found in a region called the *instability strip* (Figure 14.5). When a star's temperature and luminosity place it in this strip, the star becomes internally unstable, and both its temperature and its radius vary in a regular way, causing the pulsations we observe. Cepheid variables are high-mass, high-luminosity stars evolving across the upper part of the H–R diagram. ∞ ***(Sec. 12.4)*** The less-luminous RR Lyrae variables are lower-mass horizontal-branch (core helium fusion) stars that happen to lie within the lower portion of the instability strip. ∞ ***(Sec. 12.2)***

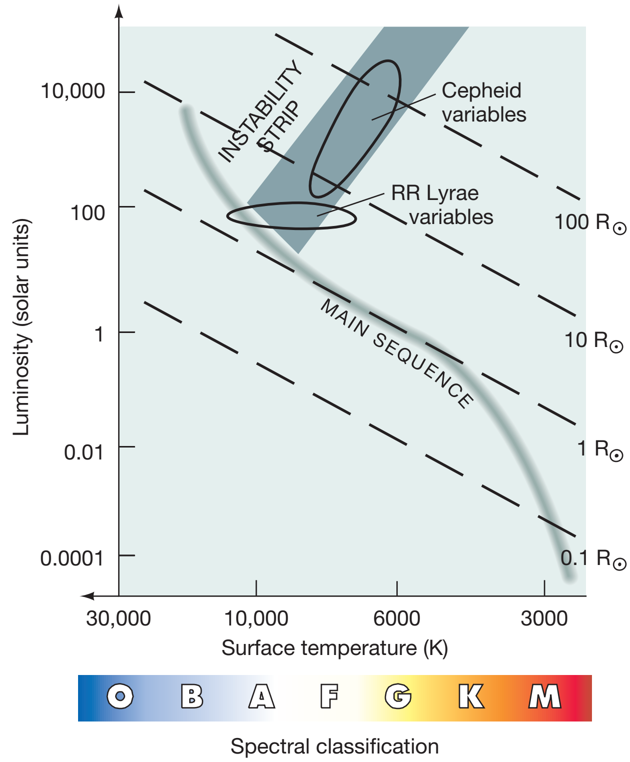
A New Yardstick

Pulsating variable stars are important to Galactic astronomy because once we recognize a star as being of the RR Lyrae or Cepheid type, we can infer its luminosity, and that in turn allows us to measure its distance. Comparing the star's (known) luminosity with its (observed) apparent brightness yields an estimate of its distance, by the inverse-square law. ∞ ***(Sec. 10.2)*** In this way, astronomers can use pulsating variables as a means of determining distances, both within our own Galaxy and far beyond.

How do we infer a variable star's luminosity? For RR Lyrae variables, this is simple. All such stars have basically the same luminosity (averaged over a complete pulsation cycle)—about 100 times that of the Sun. For Cepheids, we use a correlation between average luminosity and pulsation period, known as the **period–luminosity relationship.** In 1908, Henrietta Leavitt of Harvard College Observatory (see *Discovery 14-1*) discovered that Cepheids that vary slowly—that is, have long periods—have high luminosities, while short-period Cepheids have low luminosities. Figure 14.6 illustrates the period–luminosity relationship for Cepheids found within a thousand parsecs or so of Earth. Astronomers can plot such a diagram for nearby Cepheid variables because they can measure their distances, and hence their luminosities, using stellar or spectroscopic parallax. ∞ ***Secs. 10.1 and 10.6*** Thus, a simple measurement of a Cepheid variable's pulsation period immediately tells us its luminosity—we just read it off the graph in Figure 14.6. (The roughly constant luminosities of the RR Lyrae variables are also indicated in the figure.)

This distance-measurement technique works well provided the variable star can be clearly identified and its pulsation period measured. With Cepheids, this method allows astronomers to estimate distances out to about 25 million parsecs, more than enough to take us to the nearest galaxies. Indeed, the existence of galaxies beyond our own was first established in the late 1920s, when American astronomer Edwin Hubble observed Cepheids in the Andromeda galaxy and thereby succeeded in measuring its distance. The less luminous RR Lyrae stars are not as easily detectable as Cepheids, so their usable range is not as great. However, they are much more common, so within this limited range, they are actually more useful than Cepheids.

We began our cosmic distance ladder in Chapter 1 with radar ranging in the solar system. ∞ ***(Sec. 1.3)*** In Chapter 10, we extended it to include stellar and

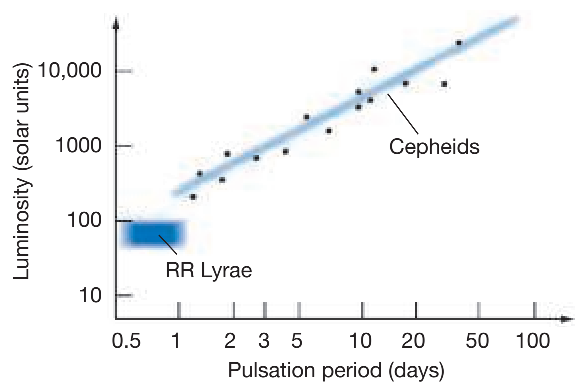


▲ **FIGURE 14.5 Variable Stars on the H–R Diagram** Pulsating variable stars are found in the instability strip of the H–R diagram. As a high-mass star evolves through the strip, it becomes a Cepheid variable. Low-mass horizontal-branch stars in the instability strip are RR Lyrae variables.

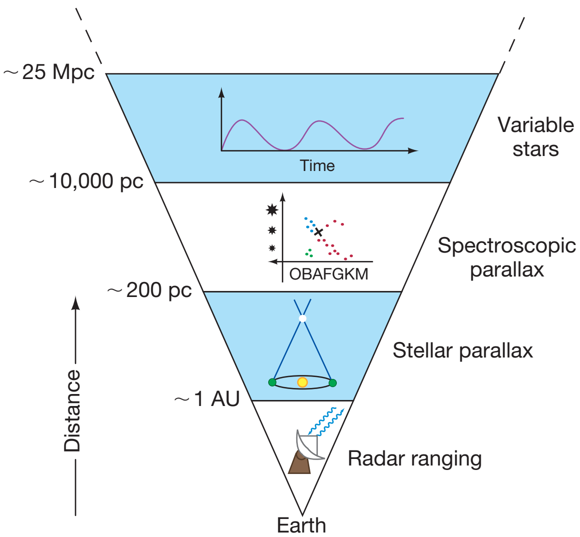
MA ANIMATION / VIDEO
Cepheid Variable Star in Distant Galaxy

CONCEPT CHECK

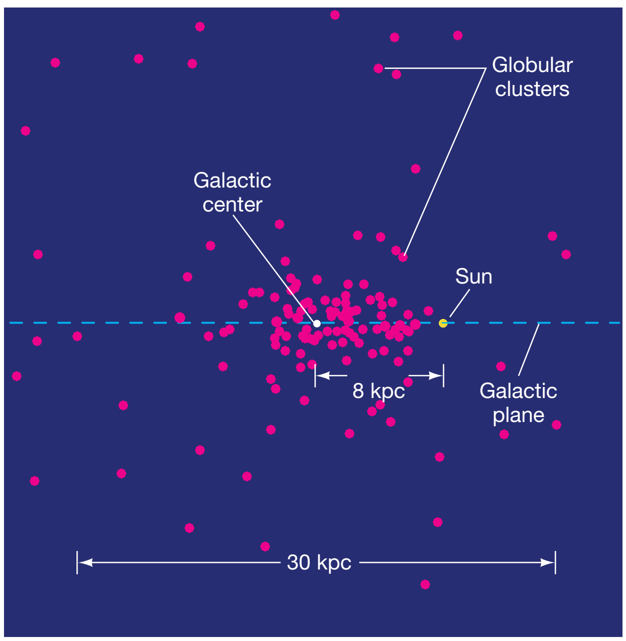
Can variable stars be used to map out the structure of the Galactic disk?



▲ **FIGURE 14.6 Period–Luminosity Relationship** A plot of pulsation period versus average absolute brightness (that is, luminosity) for a group of Cepheid variable stars. The two properties are tightly correlated. The pulsation periods of some RR Lyrae variables are also shown.



▲ **FIGURE 14.7 Variable Stars on Distance Ladder**
INTERACTIVE Application of the period–luminosity relationship for Cepheid variable stars allows estimates of distances out to about 25 Mpc with reasonable accuracy.



▲ **FIGURE 14.8 Globular Cluster Distribution** Our Sun does not coincide with the center of the very large collection of globular clusters (indicated by the pink dots). Instead, more globular clusters are found in one direction than in any other. The Sun resides closer to the edge of the collection, which measures roughly 30 kpc across. The globular clusters outline the true distribution of stars in the Galactic halo.

PROCESS OF SCIENCE CHECK

Go to a library or the Web and research the Great Debate in 1920 between Harlow Shapley and Heber Curtis on the size of our Galaxy and scale of the universe. Which viewpoint was ultimately proved right, and what were the consequences for our understanding of the cosmos?

spectroscopic parallax. ∞ *(Secs. 10.1, 10.6)* Figure 14.7 expands it further by adding variable stars as a fourth method of determining distance.

The Size and Shape of Our Galaxy

Many RR Lyrae variables are found in globular clusters, those tightly bound swarms of old, reddish stars we first met in Chapter 11. ∞ *(Sec. 11.6)* Early in the 20th century, the American astronomer Harlow Shapley used observations of RR Lyrae stars to make two very important discoveries about the Galactic globular cluster system. First, he showed that most globular clusters reside at great distances—many thousands of parsecs—from the Sun. Second, by measuring the direction and distance of each cluster, he determined their three-dimensional distribution in space (Figures 14.8 and 14.9). In this way, Shapley demonstrated that the globular clusters map out a truly gigantic, and roughly *spherical*, volume of space, now known to be about 30 kpc across. However, the center of the distribution lies nowhere near our Sun. It is located nearly 8 kpc away from us, in the constellation Sagittarius.

In a brilliant intellectual leap, Shapley realized that the distribution of globular clusters maps out the true extent of stars in the Milky Way Galaxy—the region that we now call the Galactic halo. The hub of this vast collection of matter, 8 kpc from the Sun, is the **Galactic center.** As illustrated in Figure 14.9, we live in the suburbs of this huge ensemble, in the Galactic disk—the thin sheet of young stars, gas, and dust that cuts through the center of the halo. Since Shapley's time, astronomers have identified many individual stars—that is, stars not belonging to any globular cluster—within the Galactic halo.

Shapley's bold interpretation of the globular clusters as defining the overall structure of our Galaxy was an enormous step forward in human understanding of our place in the universe. Five hundred years ago Earth was considered the center of all things. Copernicus argued otherwise, demoting our planet to an undistinguished place far from the center of the solar system. In Shapley's time the prevailing view was that our Sun was the center not only of the Galaxy but also of the universe. Shapley showed otherwise. With his observations of globular clusters, he simultaneously increased the size of our Galaxy by almost a factor of 10 over earlier estimates and banished our parent Sun to its periphery, virtually overnight!

14.3 Galactic Structure

Based on optical, infrared, and radio studies of our Galaxy, Figure 14.9 illustrates the very different spatial distributions of the disk, bulge, and halo components of the Milky Way Galaxy.

Mapping the Galaxy

The extent of the halo in Figure 14.9 is based largely on optical observations of globular clusters and other halo stars. However, as we have seen, optical techniques can cover only a small portion of the dusty Galactic disk. Much of our knowledge of the structure of the disk on larger scales is based on radio observations, particularly of the 21-cm radio emission line produced by atomic hydrogen. ∞ *(Sec. 11.3)* Because long-wavelength radio waves are largely unaffected by interstellar dust, and hydrogen is by far the most abundant element in interstellar space, the 21-cm signals are strong enough that virtually the entire disk can be observed in this way.

14.1 DISCOVERY

Early Computers

A large portion of the early research in observational astronomy focused on monitoring stellar luminosities and analyzing stellar spectra. Much of this pioneering work was done using photographic methods. What is not so well known is that most of the labor was accomplished by women. Around the turn of the 20th century, a few dozen dedicated women—assistants at the Harvard College Observatory—created an enormous database by observing, sorting, measuring, and cataloging photographic information that helped form the foundation of modern astronomy. Some of them went far beyond their duties in the lab to make many of the basic astronomical discoveries often taken for granted today.

This 1910 photograph shows several of those women carefully examining star images and measuring variations in luminosity or wavelengths of spectral lines. In the cramped quarters of the Harvard Observatory, these women inspected image after image to collect a vast body of data on hundreds of thousands of stars. Note the plot of stellar luminosity changes pasted on the wall at the left. The cyclical pattern is so regular that it likely belongs to a Cepheid variable. Known as "computers" (there were no electronic devices then), these women were paid 25 cents an hour.

(Harvard College Observatory)

In 1880 these workers began a survey of the skies that would continue for half a century. Their first major accomplishment was a catalog of the brightnesses and spectra of tens of thousands of stars, published in 1890 under the direction of Williamina Fleming. On the basis of this compilation, several of these women made fundamental contributions to astronomy. In 1897 Antonia Maury undertook the most detailed study of stellar spectra to that time, enabling Hertzsprung and Russell independently to develop what is now called the H–R diagram. In 1898 Annie Cannon proposed the spectral classification system (described in Chapter 10) that is now the international standard for categorizing stars. *(Sec. 10.5)* In 1908 Henrietta Leavitt discovered the period–luminosity relationship for Cepheid variable stars, which later allowed astronomers to recognize our Sun's true position in our Galaxy, as well as our Galaxy's true place in the universe.

According to the radio studies, the center of the gas distribution coincides roughly with the center of the globular cluster system, lying about 8 kpc from the Sun. In fact, this figure is derived most accurately from radio observations of Galactic gas. The densities of both stars and gas in the disk decline quite rapidly beyond about 15 kpc from the Galactic center (although some radio-emitting gas has been observed out to at least 50 kpc).

Perpendicular to the Galactic plane, the disk in the vicinity of the Sun is "only" about 300 pc thick, or about 1/100 of the 30-kpc Galactic diameter. Don't be fooled, though. Even if you could travel at the speed of light, it would take you 1000 years to traverse the

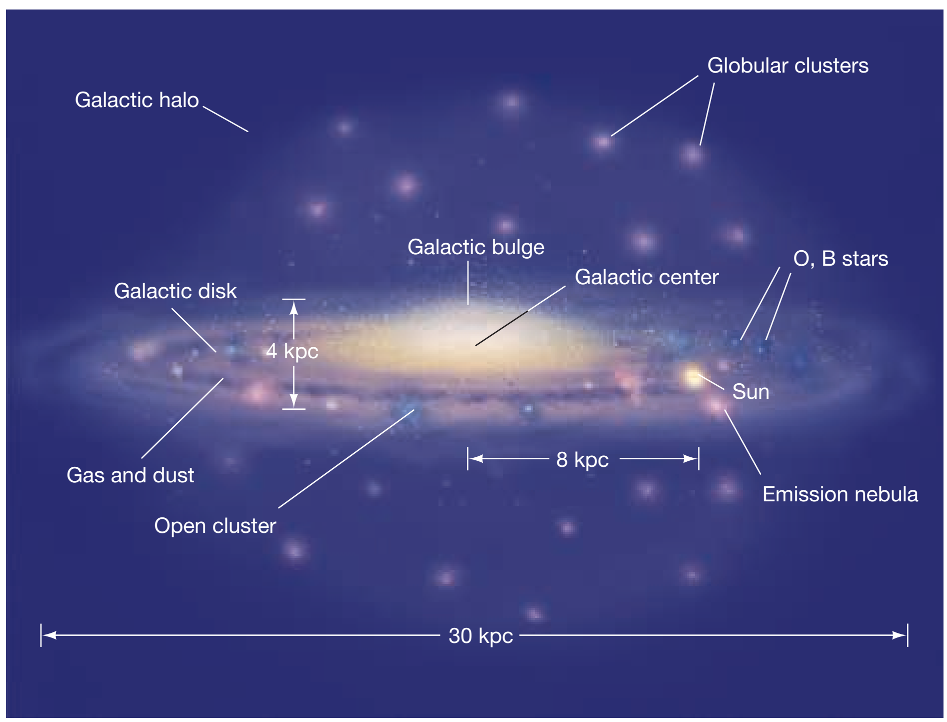
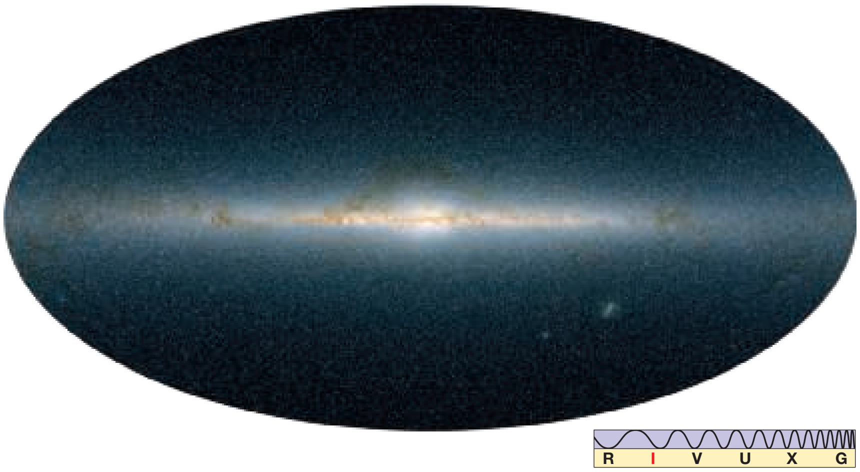


FIGURE 14.9 Stellar Populations in Our Galaxy
INTERACTIVE Artist's conception of a (nearly) edge-on view of the Milky Way Galaxy, showing schematically the distributions of young blue stars, open clusters, old red stars, and globular clusters. (The brightness and size of our Sun are greatly exaggerated for clarity.)



▲ **FIGURE 14.10 Infrared View of the Milky Way Galaxy**
INTERACTIVE A wide-angle infrared image of the disk and bulge of the Milky Way Galaxy, as observed by the Two Micron All Sky Survey. Compare Figure 14.2(c). *(Atlas Image)*

INTERACTIVE
Stellar Populations in a Star Cluster

thickness of the Galactic disk. The disk may be thin compared with the Galactic diameter, but it is huge by human standards.

Also shown in Figure 14.9 is our Galaxy's central bulge, measuring roughly 6 kpc across in the plane of the Galactic disk by 4 kpc perpendicular to that plane. Obscuration by interstellar dust makes it difficult to study the bulge at optical wavelengths. However, at longer wavelengths, which are less affected by interstellar matter, a much clearer picture emerges (compare Figure 14.10 with Figures 14.1b and 14.2c). Detailed measurements of the motion of gas and stars in and near the bulge imply that it is actually football shaped, about half as wide as it is long, with the long axis of the football lying in the Galactic plane. (In this case, our Galaxy is probably of the "barred-spiral" type—see Section 15.1.)

Stellar Populations

Aside from their shapes, the three components of the Galaxy—disk, bulge, and halo—have other properties that distinguish them from one another. First, the halo contains essentially *no* gas or dust—just the opposite of the disk and bulge, in which interstellar matter is common. Second, there are clear differences in the *colors* of the stars in the disk, bulge, and halo. Stars in the Galactic bulge and halo are distinctly redder than those found in the disk. Observations of other spiral galaxies also show this trend—the blue-white tint of the disk and the yellowish coloration of the bulge are evident in Figures 14.2(a) and (c).

All the bright, blue stars visible in our night sky are part of the Galactic disk, as are the young open star clusters and star-forming regions. In contrast, the cooler, redder stars—including those found in the old globular clusters—are more uniformly distributed throughout the disk, bulge, and halo. Galactic disks appear bluish because main-sequence O- and B-type blue supergiants are very much brighter than G-, K-, and M-type dwarfs, even though the dwarfs are present in far greater numbers.

The explanation for the marked difference in stellar content between disk and halo is that, whereas the gas-rich Galactic disk is the site of ongoing star formation and thus contains stars of all ages, all the stars in the Galactic halo are *old*. The absence of dust and gas in the halo means that no new stars are forming there, and star formation apparently ceased long ago—at least 10 billion years in the past, judging from the ages of the globular clusters. ∞ *(Sec. 12.6)* The gas density is very high in the inner part of the Galactic bulge, making this region the site of vigorous ongoing star formation, and both very old and very young stars mingle there. The bulge's gas-poor outer regions have properties more similar to those of the halo. As we will see in Chapter 15, All these statements are equally true for other spiral galaxies—young, bright stars are always found in the disk and inner bulge because the interstellar medium is densest there.

Spectroscopic studies indicate that halo stars are far less abundant in heavy elements (that is, elements heavier than helium) than are stars in the disk. Each successive cycle of star formation and evolution enriches the interstellar medium with the products of stellar evolution, leading to a steady increase in heavy elements with time. ∞ *(Sec. 12.7)* Thus, the scarcity of these elements in halo stars is consistent with the view that the halo formed long ago.

Astronomers often refer to young disk stars as *Population I* stars and old halo stars as *Population II* stars. The idea of two stellar "populations" dates back to the

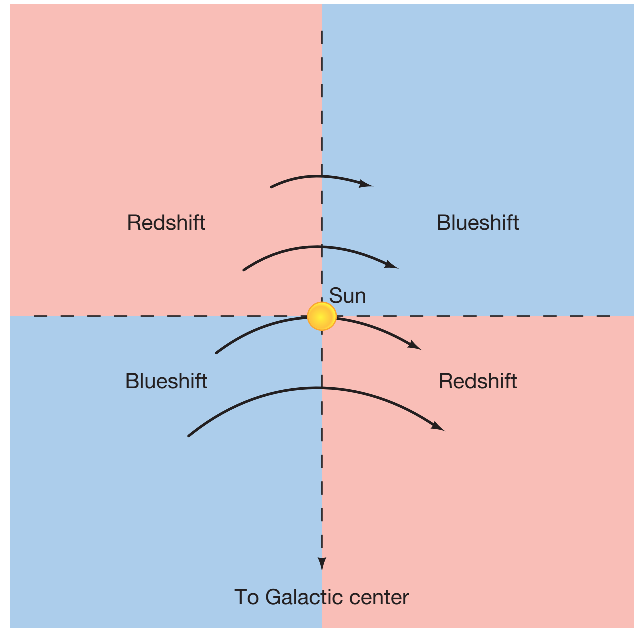
DATA POINTS

Galactic Structure

More than one-third of students had difficulty describing and distinguishing the different regions of our Galaxy. Some points to remember:

- The disk is the youngest part of our Galaxy. It is circular and highly flattened, and it is the site of ongoing star formation.
- The halo is the oldest part of our Galaxy. It is approximately spherical and consists primarily of stars formed long ago.
- The bulge contains both young and old stars. It is not as flattened as the disk but flatter than the halo.
- Stars in the disk move in roughly circular, planar orbits around the Galactic center; stars in the bulge and halo also orbit the Galactic center but move in 3 dimensions in all directions, often traveling far above or below the disk.

▶ **FIGURE 14.11 Orbital Motion in the Galactic Disk** Stars and interstellar clouds in the neighborhood of the Sun show systematic Doppler motions, implying that the disk of the Galaxy spins in a well-ordered way. These four Galactic quadrants are drawn to intersect not at the Galactic center, but at the Sun, the location from which observations are made. Because the Sun orbits faster than stars and gas at larger radii, it moves away from material at top left and gains on that at top right, resulting in the Doppler shifts indicated. Likewise, stars and gas in the bottom left quadrant are gaining on us, while material at bottom right is pulling away.



1930s, when the differences between disk and halo stars first became clear. It represents an oversimplification, as there is actually a continuous variation in stellar ages throughout the Milky Way Galaxy and not a simple division of stars into two distinct "young" and "old" categories. Nevertheless, the terminology is still widely used.

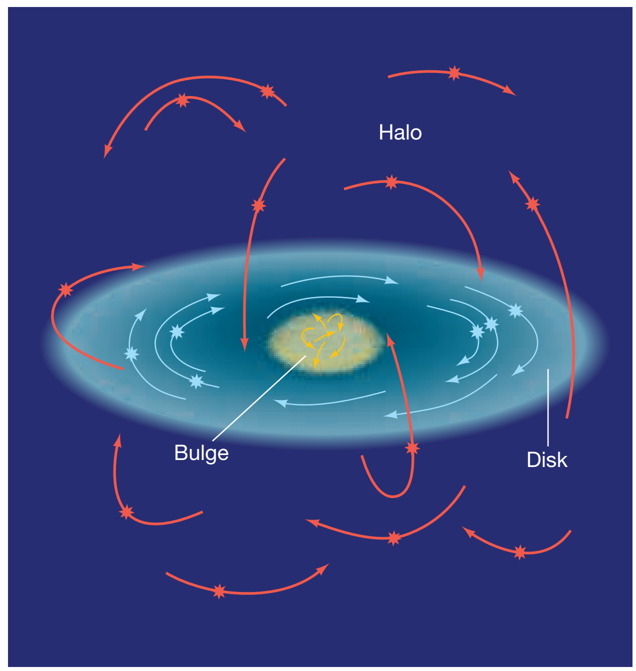
Orbital Motion

Are the internal motions of our Galaxy's members chaotic and random, or are they part of some gigantic "traffic pattern"? The answer depends on our perspective. The motion of stars and clouds we see on small scales (within a few tens of parsecs of the Sun) seems random, but on larger scales (hundreds or thousands of parsecs) the motion is much more orderly.

As we look around the Galactic disk in different directions, a clear pattern of motion emerges (see Figure 14.11). Radiation received from stars and interstellar gas clouds in the upper-right and the lower-left quadrants of Figure 14.11 is generally *blueshifted*. At the same time, radiation from stars and gas sampled in the upper-left and lower-right quadrants tends to be *redshifted*. In other words, some regions of the Galaxy (in the blueshifted directions) are approaching the Sun, while others (the redshifted ones) are receding from us. Careful study of the orbits of stars and gas clouds near the Sun leads us to the conclusion that the entire Galactic disk is *rotating* about the Galactic center. In the vicinity of the Sun, 8 kpc from the center, the orbital speed is about 220 km/s, so material takes about 225 million years to complete one circuit. At other distances from the center, the rotation period is different—shorter closer to the center, longer at greater distances—the Galactic disk rotates not as a solid object but *differentially*.

This picture of orderly circular orbital motion about the Galactic center applies only to the Galactic disk. The old globular clusters in the halo and the faint, reddish individual stars in both the halo and the bulge do *not* share the disk's well-defined rotation. Instead, as shown in Figure 14.12, their orbits are oriented randomly. Although they do orbit the Galactic center, these stars move in all directions, their paths filling an entire three-dimensional volume rather than a nearly two-dimensional disk.

At any given distance from the Galactic center, bulge or halo stars move in their orbits at speeds comparable to the disk's rotational speed at that radius. However, unlike stars in the disk, bulge and halo stars orbit in *all* directions, not just in a roughly circular path confined to a narrowly defined plane. Their orbits carry these stars repeatedly through the disk and out the other side. (They don't collide with stars in the disk because interstellar distances are huge compared with the diameters of individual stars—a star or even an entire star cluster passes through the disk almost as though it wasn't there—see *Discovery 15-1*.)



▲ **FIGURE 14.12 Stellar Orbits in Our Galaxy** Stars in the Galactic disk (blue curves) move in orderly, circular orbits about the Galactic center. In contrast, halo stars (orange curves) move randomly around the center. The orbit of a typical halo star takes it high above the Galactic disk, then down through the disk plane, then out the other side and far below the disk. Orbital properties of bulge stars are intermediate between those of the disk and halo stars.

CONCEPT CHECK

Why do astronomers regard the disk and halo as distinctly different components of our Galaxy?

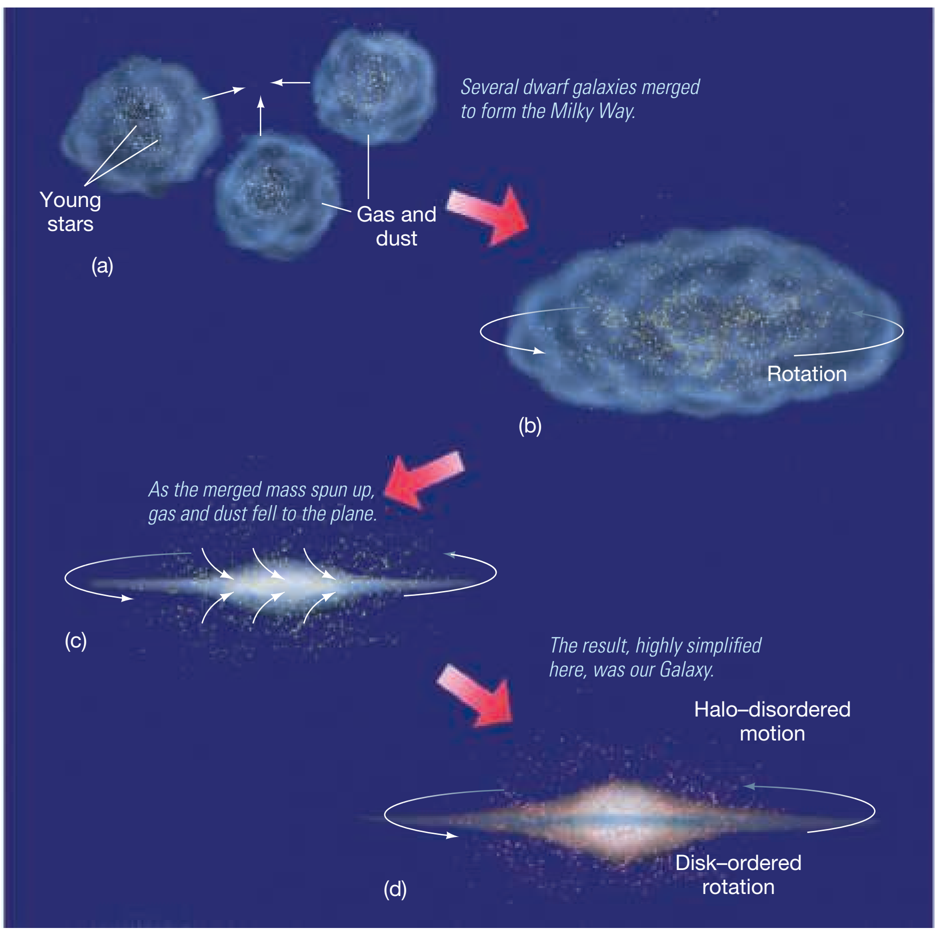
14.4 Formation of the Milky Way

Table 14.1 compares some key properties of the three basic components of the Galaxy. Is there some evolutionary scenario that can naturally account for the structure we see today? The answer is yes, and it takes us all the way back to the birth of our Galaxy, more than 10 billion years ago. For simplicity we confine our discussion here to the Galactic disk and halo. In many ways the bulge is intermediate in its properties between these two extremes.

Figure 14.13 illustrates the current view of our Galaxy's evolution. Somewhat like the star formation scenario outlined in Chapter 11 discussed earlier, it starts from an extended cloud of pregalactic gas. ∞ *(Sec. 11.4)* When the first Galactic stars and globular clusters formed, the gas in our Galaxy had not yet accumulated into a thin disk. Instead, it was spread out over an irregular region of space spanning many tens of kiloparsecs. When the first stars formed, they were distributed throughout this volume (Figure 14.13b). Their distribution today (the Galactic halo) reflects that fact—it is an imprint of their birth. Most astronomers think that the very first stars formed even earlier, in smaller systems that later merged to create our Galaxy (Figure 14.13a; see also ∞ *Section 16.4*). Many more stars were likely born during the mergers themselves, as interstellar gas clouds collided and collapsed. The present-day halo would look much the same in either case.

Since those early times, rotation has flattened the gas in our Galaxy into a thin disk (Figure 14.13c). Physically, this process is similar to the flattening of the solar nebula during the formation of the solar system, except on a vastly larger scale. ∞ *(Sec. 4.3)* Star formation in the halo ceased billions of years ago when the raw materials—interstellar gas and dust—fell to the Galactic plane. Ongoing star formation in the disk gives it its bluish tint, but the halo's short-lived blue stars died long ago leaving only the long-lived red stars that give it its characteristic pinkish glow (Figure 14.13d). The Galactic halo is ancient; the disk is full of youthful activity.

▼ **FIGURE 14.13 Milky Way Galaxy Formation** (a) The Milky Way Galaxy likely formed by a merger of several smaller systems. (b) Early on, our Galaxy was irregularly shaped, with gas distributed throughout its volume. When stars formed during this stage, their orbits carried them throughout an extended three-dimensional volume surrounding the newborn Galaxy. (c) In time, the gas and dust fell to the Galactic plane and formed a spinning disk. The stars that had already formed were left behind in the halo. (d) New stars forming in the disk inherit its overall rotation and so orbit the Galactic center on ordered, circular orbits.



Studies of the composition of stars in the Galactic disk suggest that the infall of halo gas is still going on today. The best available models of star formation and stellar evolution predict that the fraction of heavy elements in disk stars should be significantly *greater* than is actually observed, unless the gas in the disk is steadily being "diluted" by fresh gas arriving from the halo at a rate of perhaps 5–10 solar masses per year. ∞ *(Sec. 12.5)* Accumulated over billions of years, this amounts to a significant fraction of the total mass of the disk (see Section 14.6).

This theory also explains the chaotic orbits of the halo stars. When the halo developed, the irregularly shaped Galaxy was rotating very slowly, so there was no strongly preferred direction in which matter tended to move. As a result, halo stars were free to travel along nearly any path once they formed (or when their parent systems merged). As the Galactic disk formed, however, conservation of angular momentum caused it to spin more rapidly. Stars forming from the gas and dust of the disk inherit its rotational motion and so move on well-defined circular orbits.

TABLE 14.1 Overall Properties of the Galactic Disk, Halo, and Bulge

Galactic Disk	Galactic Halo	Galactic Bulge
Highly flattened	roughly spherical—mildly flattened	somewhat flattened—elongated in the plane of the disk (football-shaped)
Contains both young and old stars	contains old stars only	contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	contains no gas and dust	contains gas and dust, especially in the inner regions
Site of ongoing star formation	no star formation during the last 10 billion years	ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	stars have random orbits in three dimensions	stars have largely random orbits, but with some net rotation about the Galactic center
Spiral arms (Sec. 14.5)	little discernible substructure; globular clusters, tidal streams (Sec. 14.3)	ring of gas and dust near center; central Galactic nucleus (Sec. 14.7)
Overall white coloration, with blue spiral arms	reddish in color	yellow-white

In principle, the structure of our Galaxy bears witness to the conditions that created it. In practice, however, the sheer complexity of the system we inhabit means that the early stages of the Milky Way are still quite poorly understood. We will return to the subject of galaxy formation in Chapters 15 and 16.

CONCEPT CHECK

Why are there no young halo stars?

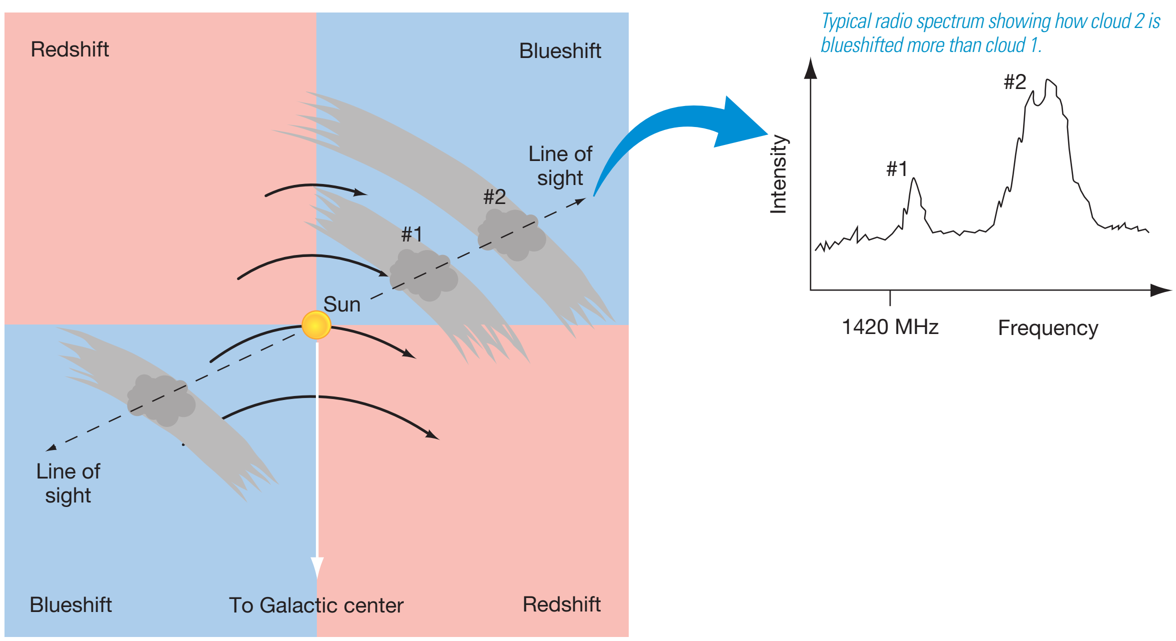
14.5 Galactic Spiral Arms

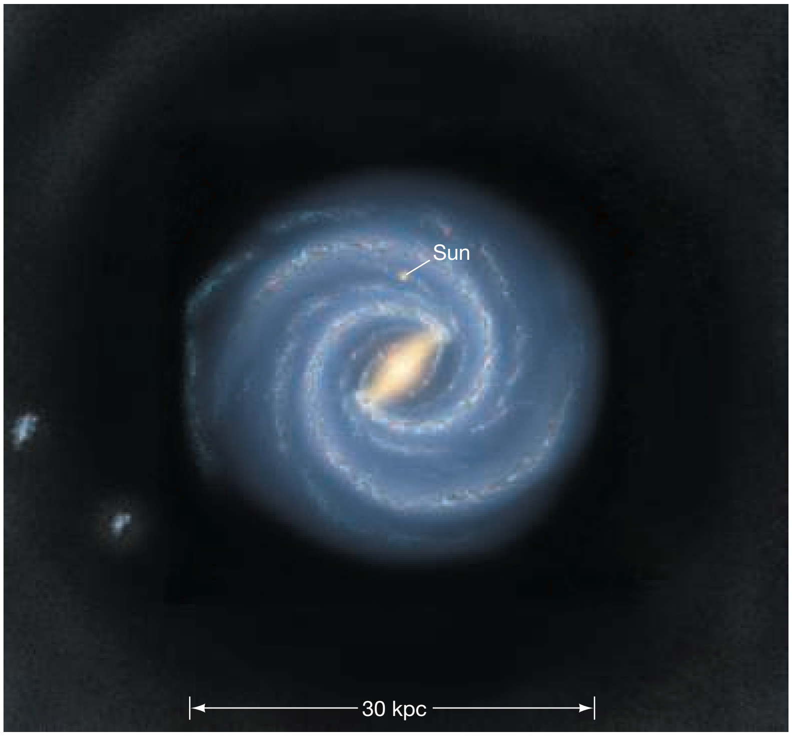
Radio studies provide perhaps the best direct evidence that we live in a spiral Galaxy. As illustrated in Figure 14.14, radio observations of interstellar gas, repeated in all directions in the Galactic plane, allow astronomers to map out its distribution and paint a detailed picture of the Galactic disk.

The Galaxy's differential rotation means that gas clouds at different distances are moving at different speeds with respect to Earth, so the radiation received from them is Doppler shifted by different amounts. Astronomers use all available data, coupled with knowledge of Newtonian mechanics, to construct a mathematical model of the rotation of stars and gas throughout the Galactic disk. *(Sec. 2.7)* The model allows us to turn a measured velocity into a distance along the line of sight. As in so many areas of astronomy, theory and observations complement one another—the data refine the theoretical model, while the model in turn provides the framework needed to understand and interpret further observations. *(Sec. 0.5)*

Figure 14.15 is an artist's conception (based on observational data) of the appearance of our Galaxy as seen from far above the disk. The figure clearly shows our Galaxy's **spiral arms,** pinwheel-like structures originating close to the Galactic bulge and extending outward throughout much of the Galactic disk. One of these arms wraps around a large part of

▼ FIGURE 14.14 Gas in the Galactic Disk Because the disk of our Galaxy is rotating differentially (inside faster than the outside), signals from different clumps of hydrogen matter along any line of sight are Doppler shifted by different amounts. Repeated observations in many different directions allow astronomers to map out the distribution of gas in our Galaxy.





▲ **FIGURE 14.15 Milky Way Spiral Structure** An artist's conception of our Milky Way Galaxy seen face-on, based on radio and infrared maps of stars, gas, and dust in the Galactic disk. The illustration is painted from the perspective of an observer 100 kpc above the Galactic plane, showing the spiral arms emanating from a bar whose length is twice its width. Everything is drawn to scale (except for the oversized yellow dot near the top, which represents our Sun). The two small blotches to the left are dwarf galaxies, called the Magellanic Clouds, which are studied in Chapter 15. *(Adapted from JPL)*

the disk and contains our Sun. Notice, incidentally, the scale markers on Figures 14.8, 14.9, and 14.15. The Galactic globular-cluster distribution (shown in Figure 14.8), the luminous stellar component of the disk (Figure 14.9), and the known spiral structure (Figure 14.15) all have roughly the same diameter—about 30 kpc. This diameter is fairly typical of spiral galaxies observed elsewhere in the universe.

The spiral arms in our Galaxy are made up of much more than just interstellar gas and dust. Studies of the Galactic disk within a kiloparsec or so of the Sun indicate that young stellar and prestellar objects—emission nebulae, O- and B-type stars, and recently formed open clusters—are also distributed in a spiral pattern that closely follows the distribution of interstellar clouds. The obvious conclusion is that the spiral arms are the part of the Galactic disk where star formation takes place. The brightness of the young stellar objects just listed is the main reason that the spiral arms of other galaxies are easily seen from afar (Figure 14.2b).

A central problem in understanding spiral structure is explaining how that structure persists over long periods of time. The basic issue is simple: differential rotation makes it impossible for any large-scale structure "tied" to the disk material to survive. Figure 14.16 shows how a spiral pattern always consisting of the same group of stars and gas clouds would necessarily "wind up" and disappear within a few hundred million years. How then do the Galaxy's spiral arms retain their structure over long periods of time despite differential rotation? A leading explanation for the existence of spiral arms is that they are **spiral density waves**—coiled waves of gas compression that move through the Galactic disk, squeezing clouds of interstellar gas and triggering the process of star formation as they go. ∞ *(Sec. 11.4)* Like traffic slowing as it passes an obstacle on the highway (see *Discovery 14-2*), Galactic gas slows down and becomes denser as it passes through the wave. The spiral arms we observe are defined by the denser-than-normal clouds of gas thus created and by the new stars formed as a result of the spiral waves' passage.

This explanation of spiral structure avoids the problem of differential rotation because the wave pattern is not tied to any particular piece of the Galactic disk. The spirals we see are merely patterns moving through the disk, not matter being transported from place to place. The density wave moves through the collection of stars and gas making up the disk just as a sound wave moves through air or an ocean wave passes through water, compressing different parts of the disk at different times. Even though the rotation rate of the disk material varies with distance from the Galactic center, the wave itself remains intact, defining the Galaxy's spiral arms.

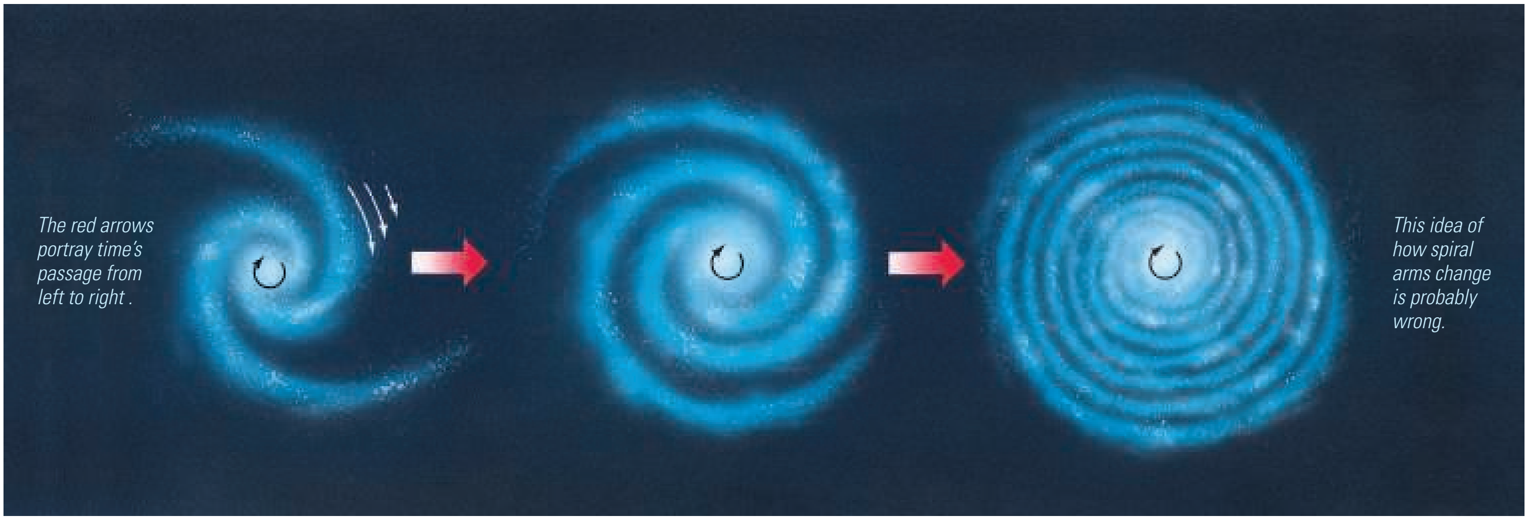
INTERACTIVE
Spiral Arms and Star Formations

Over much of the visible portion of the Galactic disk (within about 15 kpc of the center), the spiral wave pattern is predicted to rotate *more slowly* than the stars and gas. Thus, as shown in Figure 14.17, Galactic material catches up with the wave, is temporarily slowed down and compressed by the wave's gravitational pull as it passes through, then continues on its way.

As the density wave enters the arm from behind, the gas is compressed and forms stars. Dust lanes mark the regions of highest-density gas. The most prominent stars—the bright O- and B-type blue giants—live for only a short time, so emission nebulae and young star clusters are found only within the arms, near their birth sites, just ahead of the dust lanes. Their brightness emphasizes the spiral structure. Further downstream, ahead of the spiral arms, we see mostly older stars and star clusters, which have had enough time since their formation to pull ahead of the wave. Over millions of years their random individual motions, superimposed on the overall rotation around the Galactic center, distort and

CONCEPT CHECK

Why can't spiral arms simply be clouds of gas and young stars orbiting the Galactic center?

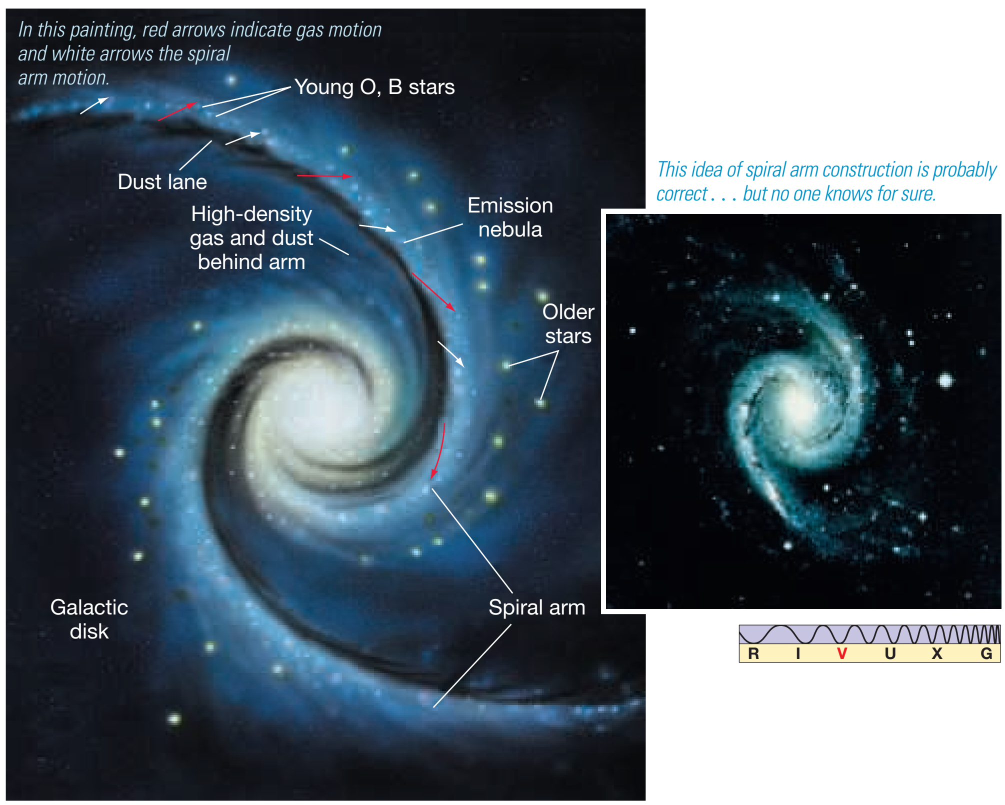


▲ **FIGURE 14.16 Differential Galactic Rotation** INTERACTIVE
The disk of our Galaxy rotates differentially, as shown by the small white arrows that represent the angular speed of the disk. If spiral arms were somehow tied to the material of the Galactic disk, such uneven rotation would cause the spiral pattern to wind up and disappear in a few hundred million years. Spiral arms would be too short-lived to be consistent with the numbers of spiral galaxies we observe today.

eventually destroy their original spiral configuration, and they become part of the general disk population.

Note, incidentally, that although the spirals shown in Figure 14.17 have two arms each, astronomers are not completely certain how many arms make up the spiral structure in our Galaxy. The theory makes no strong predictions on this point. As illustrated in Figure 14.15, the best available data suggest that our Galaxy has two major arms.

An alternative possibility is that the formation of stars drives the waves, instead of the other way around. Imagine a row of newly formed massive stars somewhere in the disk. The emission nebula created when these stars form, and the supernovae when they die, send shock waves through the surrounding gas, possibly triggering new star formation. ∞ *(Sec. 12.7)* Thus, as illustrated in Figure 14.18(a), the formation of one group of stars provides the mechanism for the creation of more stars. Computer simulations suggest that it is possible for the "wave" of star formation thus created to take on the form of a partial spiral and for this pattern to persist for some time. However, this process, known as **self-propagating star formation,** can produce only pieces of spirals, as are seen in some galaxies (Figure 14.18b). It apparently cannot produce the galaxywide spiral arms seen in other galaxies and present in our own. It may well be that there is more than one process at work in the spectacular spirals we see.



▶ **FIGURE 14.17 Spiral Density Waves**
Density-wave theory holds that the spiral arms seen in our own and many other galaxies are waves of gas compression and star formation moving through the material of the galactic disk. Gas enters an arm from behind, is compressed, and forms stars. The spiral pattern is delineated by dust lanes, regions of high gas density, and newly formed bright stars. The inset at right shows the spiral galaxy NGC 1566, which displays many of the features just described. *(AURA)*

14.2 DISCOVERY

Density Waves

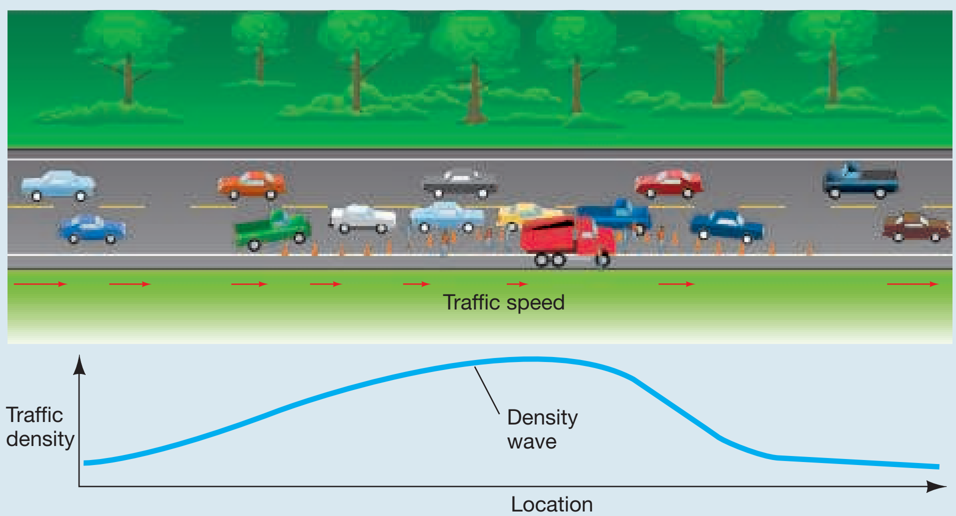
In the late 1960s, American astrophysicists C. C. Lin and Frank Shu proposed a way in which spiral arms in the Galaxy could persist for many Galactic rotations. They argued that the arms themselves contain no “permanent” matter. They should not be viewed as assemblages of stars, gas, and dust moving intact through the disk because such structures would quickly be destroyed by differential rotation. Instead, as described in the text, a spiral arm should be envisaged as a *density wave*—a wave of alternating compression and expansion sweeping through the Galaxy.

A wave in water builds up material temporarily in some places (crests) and lets it down in others (troughs). Similarly, as Galactic matter encounters a spiral density wave, the matter is compressed to form a region of higher than normal density. The matter enters the wave, is temporarily slowed down (by gravity) and compressed as it passes through, then continues on its way. This compression triggers the formation of new stars and nebulae. In this way, the spiral arms are formed and reformed repeatedly, without wrapping up.

The accompanying figure illustrates the formation of a density wave in a more familiar context—a traffic jam triggered by the presence of a repair crew moving slowly down the road. Cars slow down temporarily as they approach the crew, then speed up again as they pass the worksite and continue on their way. The result observed by a traffic helicopter flying overhead is a region of high traffic density concentrated around the work crew and moving with it. An observer on the side of the road, however, sees that the jam never contains the same cars for very long. Cars constantly catch up to the bottleneck, move slowly through it, then speed up again, only to be replaced by more cars arriving from behind.

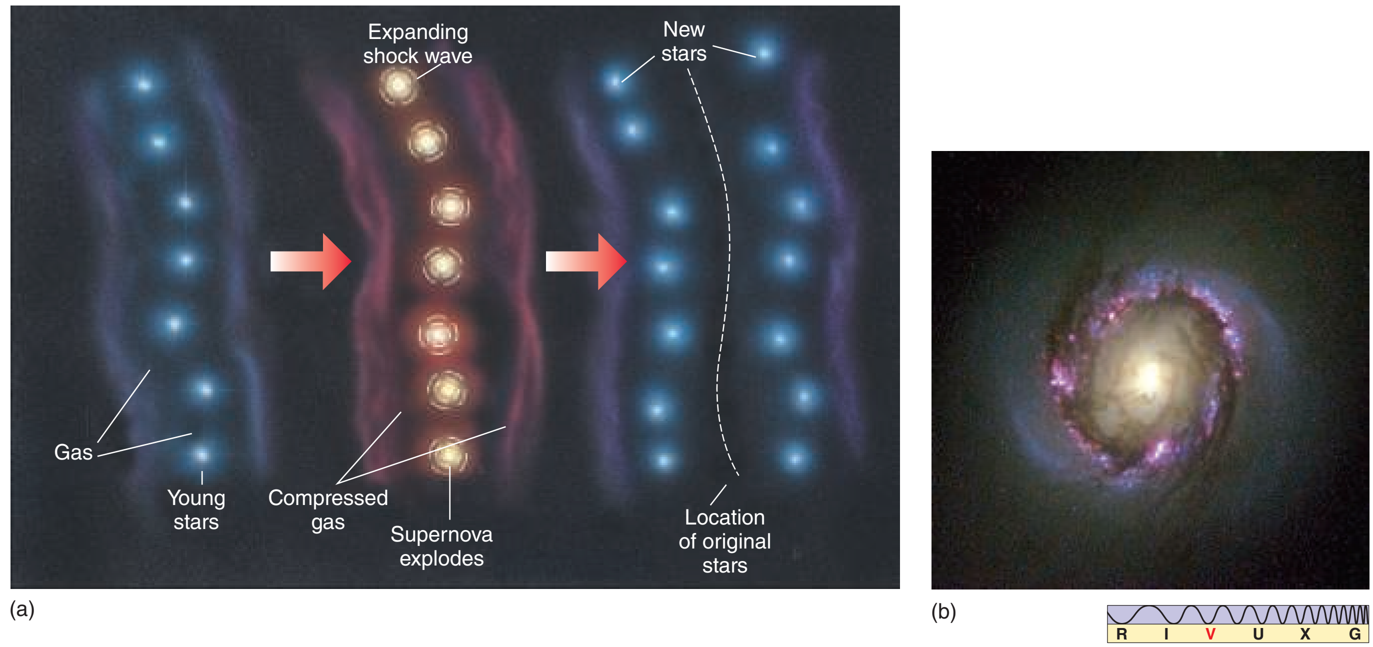
The traffic jam is analogous to the region of high stellar density in a Galactic spiral arm. Just as the traffic density wave is not tied to any particular group of cars, the spiral arms are not attached to any particular piece of disk material. Stars and gas enter a spiral arm, slow down for a while, then exit the arm and continue on their way around the Galactic center. The result is a moving region of high stellar and gas density, involving different parts of the disk at different times. Notice also that, just as in our Galaxy, the traffic jam wave moves more slowly than, and independently of, the overall traffic flow.

We can extend our traffic analogy a little further. Most drivers are well aware that the effects of such a tie-up can persist long after the road crew has stopped work and gone home for the night. Similarly, spiral density waves can continue to move through the disk even after the disturbance that originally produced them has long since subsided. According to spiral density wave theory, this is precisely what has happened in the Milky Way Galaxy. Some disturbance in the past—an encounter with a satellite galaxy, perhaps, or the effect of the central bar—produced a wave that has been moving through the Galactic disk ever since.



An important question, but one not answered by either of the two theories just described, is, Where do these spirals come from? What was responsible for generating the density wave in the first place or for creating the line of newborn stars whose evolution drives the advancing spiral arm? Scientists speculate that (1) instabilities in the gas near the galactic bulge, (2) the gravitational effects of nearby galaxies, or (3) the elongated shape of the bulge itself may have had a big

Again, time unfolds left to right, creating new stars over and over . . .



▲ **FIGURE 14.18 Self-Propagating Star Formation** (a) In this theory of the formation of spiral arms, the shock waves produced by the formation and later evolution of a group of stars provide the trigger for new rounds of star formation. (b) This process may well be responsible for the partial spiral arms seen in some galaxies, such as NGC 4314, shown here in true color. Its distinct blue appearance derives from the vast numbers of young stars that pepper its ill-defined spiral arms. *(R. Gendler)*

enough influence on the disk to get the process going. The fact is that we still don't know for sure how galaxies—including our own—acquire such beautiful spiral arms.

14.6 The Mass of the Milky Way Galaxy

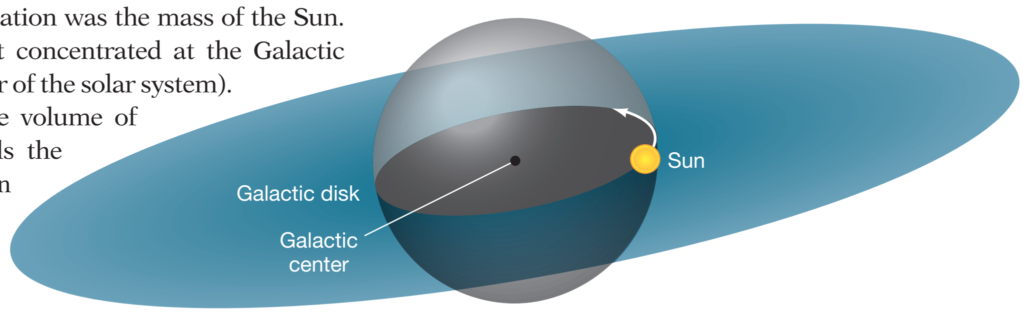
We can measure our Galaxy's mass by studying the motions of gas clouds and stars in the Galactic disk. Recall from Chapter 1 that Kepler's third law (as modified by Newton) connects the orbital period, orbit size, and masses of any two objects in orbit around one another:

$$\text{total mass (solar masses)} = \frac{\text{orbit size (astronomical units)}^3}{\text{orbit period (years)}^2}$$

The distance from the Sun to the Galactic center is about 8 kpc, and the Sun's orbital period is 225 million years. Plugging these numbers into the equation, we find a mass of almost 10^{11} solar masses—100 *billion* times the mass of our Sun.

But what mass have we just measured? When we performed the analogous calculation in the case of a planet orbiting the Sun, there was no ambiguity: Neglecting the planet's mass, the result of our calculation was the mass of the Sun. ∞ *(Sec. 1.4)* However, the Galaxy's matter is not concentrated at the Galactic center (as the Sun's mass is concentrated at the center of the solar system). Instead, Galactic matter is distributed over a large volume of space. What portion of the Galaxy's mass controls the Sun's orbit? Isaac Newton answered this question three centuries ago: The Sun's orbital period is determined by the portion of the Galaxy that lies *within the orbit of the Sun* (Figure 14.19). This is the mass computed from the above equation.

▼ **FIGURE 14.19 Weighing the Galaxy** The orbital speed of a star or gas cloud moving around the Galactic center is determined only by the mass of the Galaxy lying inside the orbit (within the gray-shaded sphere). Thus, to measure the Galaxy's total mass, we must observe objects orbiting at large distances from the center.



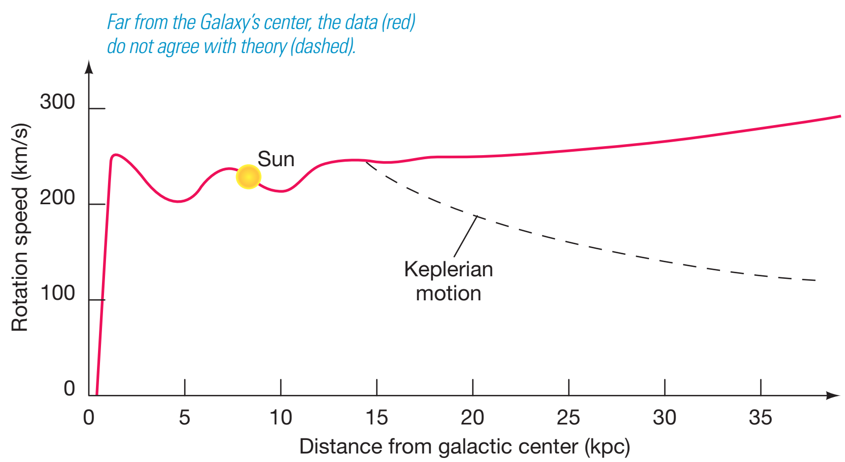
Dark Matter

To determine the mass of the Galaxy on larger scales, we must measure the orbital motion of stars and gas at greater distances from the Galactic center. Astronomers have found that the most effective way to do this is to make radio observations of gas in the Galactic disk, because radio waves are relatively unaffected by interstellar absorption and allow us to probe to great distances. On the basis of these studies, radio astronomers have determined our Galaxy's rotation rate at various distances from the Galactic center. The resultant plot of rotation speed versus distance from the center (Figure 14.20) is called the Galactic **rotation curve.**

Using the Galactic rotation curve, we can now repeat our earlier calculation to compute the total mass that lies within any distance from the Galactic center. We find, for example, that the mass within about 15 kpc from the center—the volume defined by the globular clusters and the known spiral structure—is roughly 2×10^{11} solar masses, about twice the mass contained within the Sun's orbit. Does the distribution of matter in the Galaxy end at 15 kpc, where the luminosity drops off sharply? Surprisingly, the answer is no.

If all of the mass of the Galaxy were contained within the edge of the visible structure, Newton's laws of motion predict that the orbital speed of stars and gas beyond 15 kpc would decrease with increasing distance from the Galactic center, just as the orbital speeds of the planets diminish as we move outward from the Sun. The dashed line in Figure 14.20 indicates how the rotation curve should look in that case. However, the actual rotation curve is quite different. Far from declining at larger distances, it *rises* slightly out to the limits of our measurement capabilities. This implies that the amount of mass contained within successively larger radii continues to grow beyond the orbit of the Sun, apparently out to a distance of at least 50 kpc.

According to the equation above, the amount of mass within 50 kpc is approximately 6×10^{11} solar masses. Since 2×10^{11} solar masses lies within 15 kpc of the Galactic center, we have to conclude that at least twice as much mass lies *outside* the luminous part of our Galaxy—the part made up of stars, star clusters, and spiral arms—as lies inside!



▲ **FIGURE 14.20 Galaxy Rotation Curve** The rotation curve for the Milky Way Galaxy plots rotation speed against distance from the Galactic center. The dashed curve is the rotation curve expected if the Galaxy "ended" abruptly at a radius of 15 kpc, the limit of most of the known spiral structure. The fact that the red curve does not follow this dashed line, but instead stays well above it, indicates that there must be additional unseen matter beyond that radius.

Based on these observations, astronomers conclude that the luminous portion of the Milky Way Galaxy—the region outlined by the globular clusters and by the spiral arms—is merely the "tip of the Galactic iceberg." Our Galaxy is in reality very much larger. The luminous region is surrounded by an extensive, invisible **dark halo,** which dwarfs the inner halo of stars and globular clusters and extends well beyond the 15-kpc radius once thought to represent the limit of our Galaxy. But what is this dark halo made of? We do not detect enough stars or interstellar matter to account for the mass that our computations tell us must be there. We are inescapably drawn to the conclusion that most of the mass in our Galaxy (and, as we will see, of all galaxies) exists in the form of invisible **dark matter,** whose gravitational effects we can measure and quantify, but whose precise nature we do not understand.

The term *dark* here does not refer just to matter undetectable in visible light. The material has (so far) escaped detection at *all* electromagnetic wavelengths, from radio to gamma rays. Only by its gravitational pull do we know of its existence. Dark matter is not hydrogen gas (atomic or molecular), nor is it made up of ordinary stars. Given the amount of matter that must be accounted for, we would have been able to detect it with present-day equipment if it were in either of those forms. Its composition and its consequences for the evolution of galaxies and the universe are among the most important questions in astronomy today.

Many candidates have been suggested for this dark matter, although none is proven. Among the strongest "stellar" contenders are brown dwarfs and white dwarfs. ∞ *(Secs. 11.5, 12.3)* These objects could in principle exist in great numbers throughout the Galaxy, yet would be exceedingly hard to see. Note that the ultimate "dark" candidates—black holes—are not thought to contribute much to the dark matter total, simply because the massive stars that produce them are too rare. Only about 1 star in 10,000 ends up as a black hole.

A radically different alternative is that the dark matter is made up of exotic *subatomic particles* that pervade the entire universe. In order to account for the properties of dark matter, these particles must have mass (to produce the observed gravitational effects) but otherwise interact hardly at all with "normal" matter (because otherwise we would be able to see them).[1] Many astrophysicists think that such particles could have been produced in abundance during the very earliest moments of our universe. If they survived to the present day, there might be enough of them to account for all the dark matter we think must be out there. These ideas are hard to test, however, because such particles would be very difficult to detect. Several detection experiments have been attempted, so far without success.

A few astronomers have proposed a very different explanation for the "dark matter problem," suggesting that its resolution may lie not in the nature of dark matter, but rather in a modification to Newton's law of gravity that increases the gravitational force on very large (galactic) scales, doing away with the need for dark matter in the first place. The vast majority of scientists do *not* accept this view, but the very fact that it has been proposed—and is being seriously discussed in (some) scientific circles—underscores our current level of uncertainty. Dark matter is one of the great unsolved mysteries in astronomy today.

PROCESS OF SCIENCE CHECK

The nature of subatomic dark matter particles is completely unknown, yet most scientists regard these particles as the best solution to the dark matter problem. How do you think these statements square with the experimental scientific method presented in Chapter 0?

The Search for Stellar Dark Matter

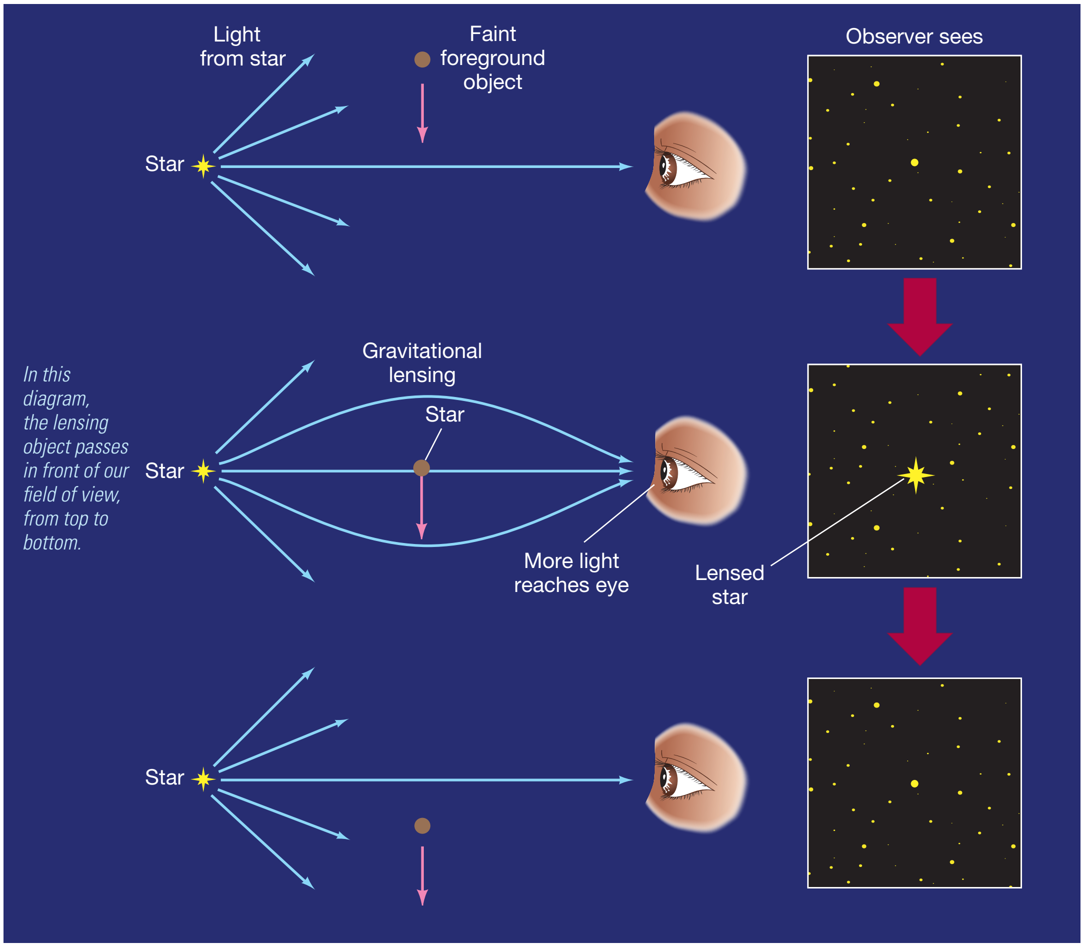
Researchers have gained insight into the distribution of stellar dark matter by using a key element of Albert Einstein's theory of general relativity—the prediction that a beam of light can be deflected by a gravitational field, which has already been verified in the case of starlight passing close to the Sun. ∞ *(More Precisely 13-2)* Although this effect is small, it has the potential for making otherwise invisible stellar objects observable from Earth. Here's how.

Imagine looking at a distant star as a faint foreground object (such as a brown dwarf or a white dwarf) happens to cross your line of sight. As illustrated in Figure 14.21, the intervening object deflects a little more starlight than usual toward you, resulting in a temporary, but quite substantial, *brightening* of the distant star. Because the effect is in some ways like the focusing of light by a lens, this process is known as **gravitational lensing.** The foreground object is referred to as a *gravitational lens*. The amount of brightening and the duration of the effect depend on the mass, distance, and speed of the lensing object. Typically, the apparent brightness of the background star increases by a factor of 2 to 5 for a period of several weeks. Thus, even though the foreground object cannot be seen directly, its effect on the light of the background star makes it detectable.

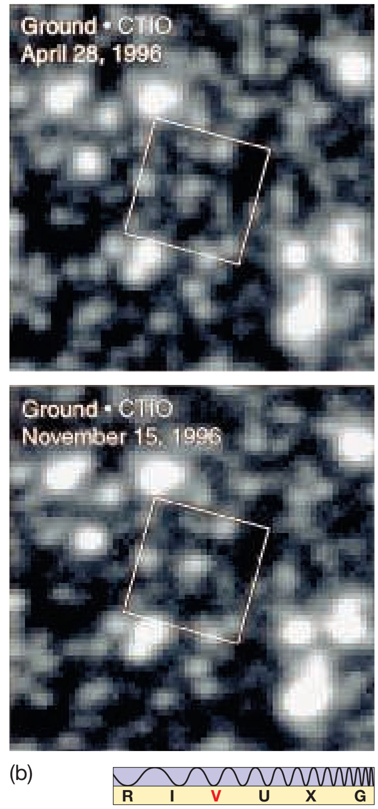
MA SELF-GUIDED TUTORIAL
Gravitational Lensing

Of course, the probability of one star passing almost directly in front of another, as seen from Earth, is extremely small. However, by observing millions of

[1] One class of candidate particles satisfying these requirements has been dubbed *W*eakly *I*nteracting *M*assive *P*articles, or WIMPs. Not to be outdone, astronomers searching for the more mundane stellar dark matter have labeled them *MA*ssive *C*ompact *H*alo *O*bjects, or MACHOs. Who says astronomers don't have a sense of humor?



(a)



(b)

▲ **FIGURE 14.21 Gravitational Lensing** (a) Gravitational lensing by a faint foreground object (such as a brown dwarf) can temporarily cause a background star to brighten significantly, providing a means of detecting otherwise invisible stellar dark matter. (b) These two images show the brightening of a star during a lensing event, this one implying that a massive, but unseen, object passed in front of the unnamed star at the center of the two boxes imaged 6 months apart. *(AURA)*

CONCEPT CHECK

In what sense is dark matter "dark"?

stars every few days over a period of years (using automated telescopes and high-speed computers to reduce the burden of coping with so much data), astronomers have so far seen thousands of events. The observations are consistent with lensing by low-mass white dwarfs and suggest that such stars could account for at least half—but apparently not all—of the Galactic dark matter inferred from dynamical studies.

Bear in mind, though, that the identity of the dark matter is not necessarily an "all-or-nothing" proposition. It is quite possible that more than one type of dark matter exists. For example, most of the dark matter in the inner (visible) parts of galaxies could be in the form of low-mass stars, while the dark matter farther out might be primarily in the form of exotic particles. We will return to this perplexing problem in later chapters.

14.7 The Galactic Center

Theory predicts that the Galactic bulge, and especially the region close to the Galactic center, should be densely populated with billions of stars. However, we are unable to see this region of our Galaxy—the interstellar medium in the Galactic disk shrouds what otherwise would be a stunning view. Figure 14.22 shows the (optical) view we do have of the region of the Milky Way toward the Galactic center, in the general direction of the constellation Sagittarius.

Galactic Activity

With the help of infrared and radio techniques we can peer more deeply into the central regions of our Galaxy than we can by optical means. Infrared observations (Figure 14.22 inset) show that the innermost parsec of our Galaxy harbors a dense cluster containing roughly 1 million stars. That's a stellar density about 100 *million* times greater than in our solar neighborhood, high enough that stars must experience frequent close encounters and even collisions.

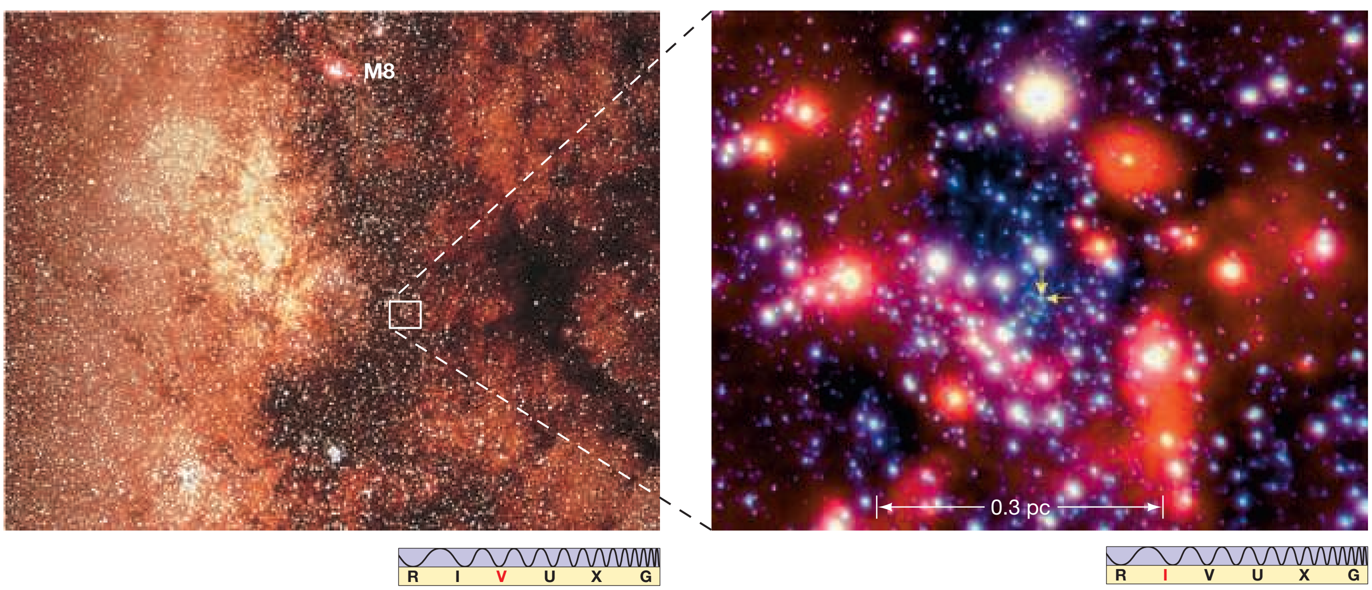
Figure 14.23(a) is an infrared view of part of Figure 14.22, with the Galactic plane now horizontal. On this scale, infrared radiation has been detected from what appear to be huge clouds rich in dust. Radio observations indicate a ring of molecular gas nearly 400 pc across, containing hundreds of thousands of solar masses of material and rotating around the Galactic center at about 100 km/s. Its origin is unclear, although researchers think that the gravity of the Galaxy's central rotating bar may deflect gas from farther out into the dense central regions.

Higher-resolution radio studies show much more structure. Figure 14.23(b) shows a region called Sagittarius A. (The name just means that it is the brightest radio source in Sagittarius.) It lies at the center of the boxed region in Figures 14.22 and 14.23(a) and, we think, at the center of our Galaxy. On a scale of about 25 pc, extended filaments can be seen. Their presence suggests to many astronomers that strong magnetic fields operate near the center, creating structures similar in appearance to (but much larger than) those observed on the active Sun.

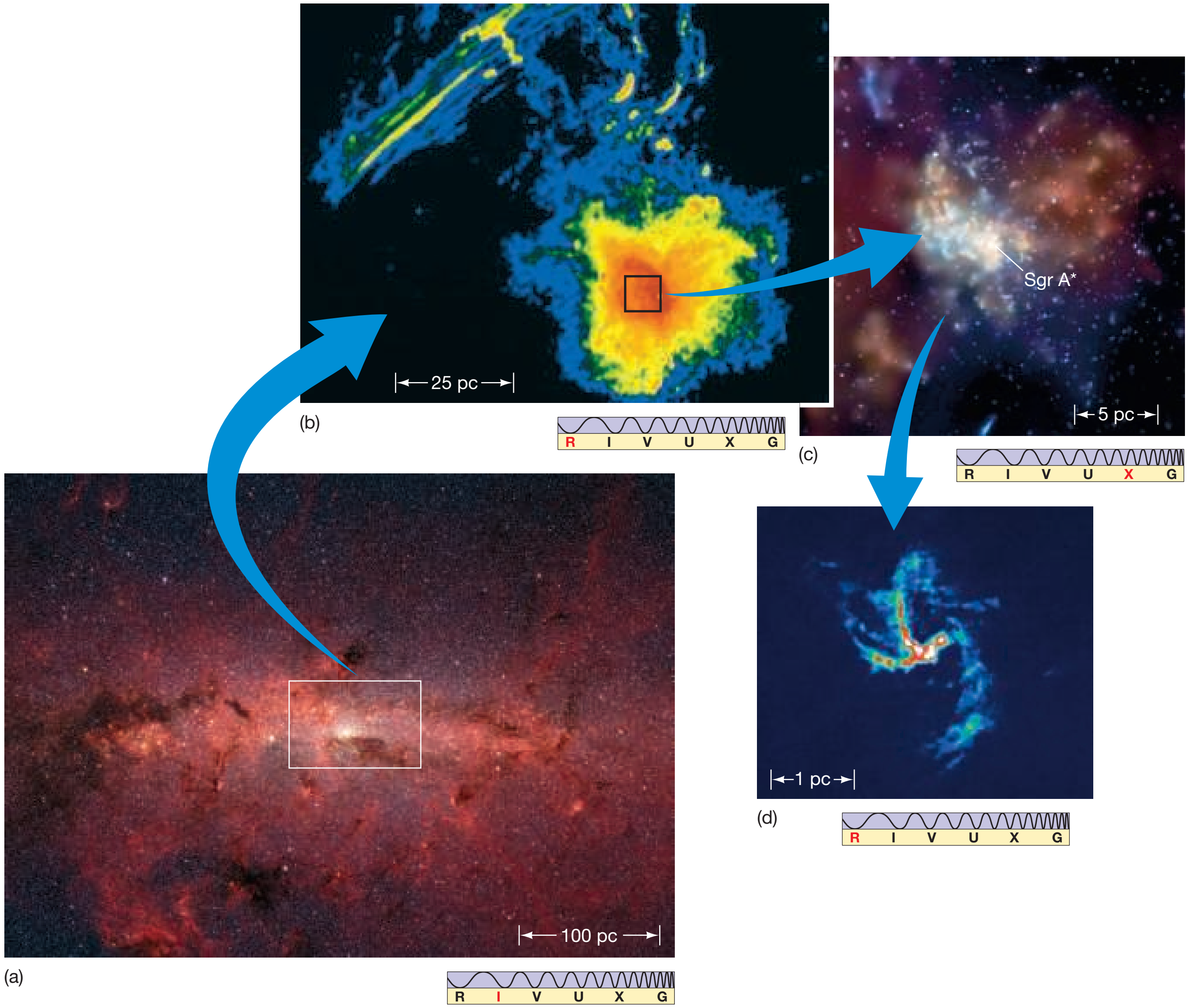
On even smaller scales (Figure 14.23c), *Chandra* observations indicate an extended region of hot X-ray-emitting gas, apparently associated with a supernova remnant, in addition to many other individual bright X-ray sources. Within that region lies a rotating ring of star-forming molecular gas only a few parsecs across, with streams of matter spiraling inward toward the center (Figure 14.23d).

What could cause all this activity? An important clue comes from the Doppler broadening of infrared spectral lines emitted from the central swirling whirlpool of gas. The extent of the broadening indicates that the gas is moving very rapidly. In order to keep this gas in orbit, whatever is at the center must be extremely massive—several million solar masses. Given the twin requirements of large mass and small size, a leading contender is a *supermassive black hole*. The strong magnetic fields are thought to be generated within the accretion disk around the black hole as matter spirals inward and may act as "particle accelerators," creating the extremely high-energy particles detected on Earth as *cosmic rays*. ∞ *(Sec. 13.3)*

MA INTERACTIVE
Spiral Galaxy M81



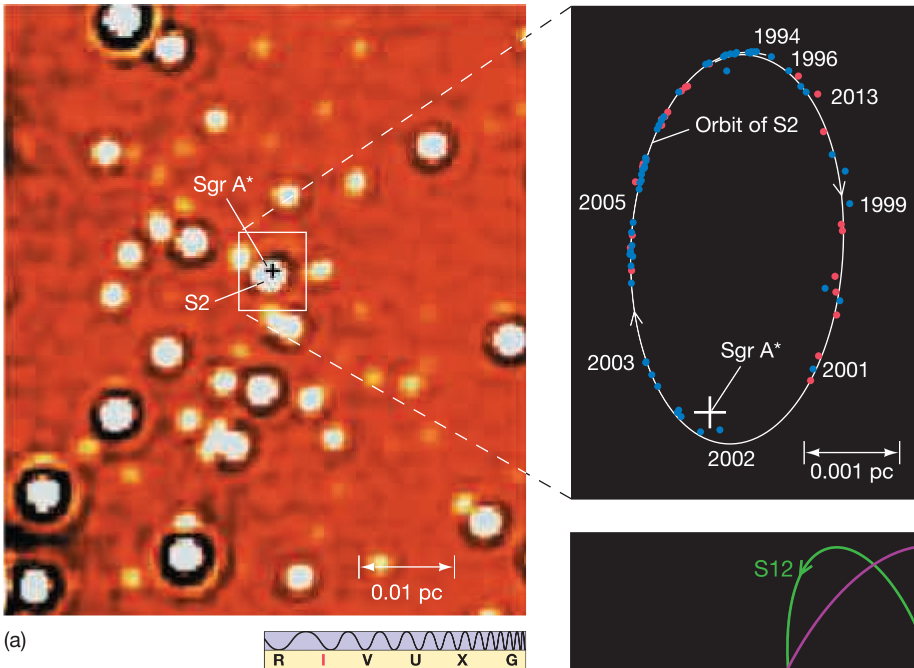
▼ **FIGURE 14.22 Galactic Center** **INTERACTIVE** Photograph of stellar and interstellar matter in the direction of the Galactic center. The field is roughly 20°, top to bottom, and is a continuation of the bottom part of Figure 11.5. The overlaid box indicates the location of the center of our Galaxy. The inset shows an adaptive-optics infrared view of the dense stellar cluster surrounding the Galactic center, whose very core is indicated by the twin arrows. *(AURA; ESO)*



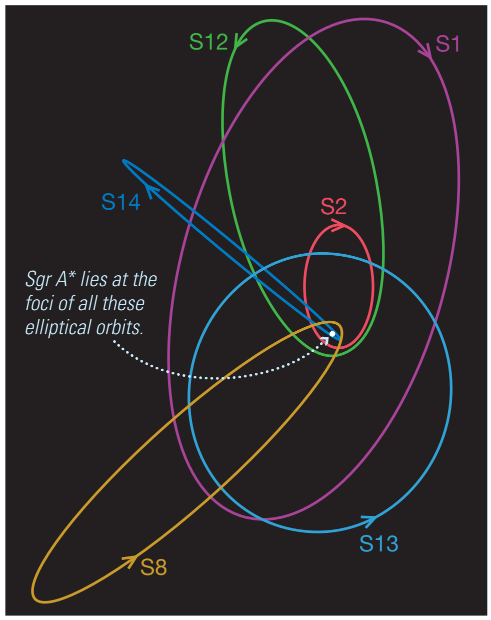
▲ **FIGURE 14.23** **Galactic Center Close-up** INTERACTIVE (a) An infrared image of the region around the center of our Galaxy shows many bright stars packed into a relatively small volume. (b) The central portion of our Galaxy, as observed in the radio part of the spectrum, shows a region about 100 pc across surrounding the Galactic center (which lies within the orange-yellow region at bottom right). The long-wavelength radio emission cuts through the Galaxy's dust, providing a view of matter in the immediate vicinity of the Galaxy's center. (c) This *Chandra* X-ray image shows the relation of a hot supernova remnant (red) and Sgr A*, the suspected black hole at the very center of our Galaxy. (d) The spiral pattern of radio emission arising from Sagittarius A itself suggests a rotating ring of matter only a few parsecs across. All images are false color, since they lie outside the visible spectrum. *(SST; NRAO; NASA)*

The Central Black Hole

At the very center of our Galaxy, at the heart of Sagittarius A, lies a remarkable object with the odd-sounding name **Sgr A*** (pronounced "saj A star"). By the standards of the active galaxies to be studied in Chapter 15, this compact **Galactic nucleus** is not particularly energetic. Still, radio observations made during the past two decades, along with more recent X- and gamma-ray observations, suggest that it is nevertheless a pretty violent place. Its total energy output (at all wavelengths) is estimated to be W, which is more than a million times that of the Sun. Very-long-baseline interferometry (VLBI) observations using radio telescopes arrayed from Hawaii to Massachusetts imply that Sgr



(a)

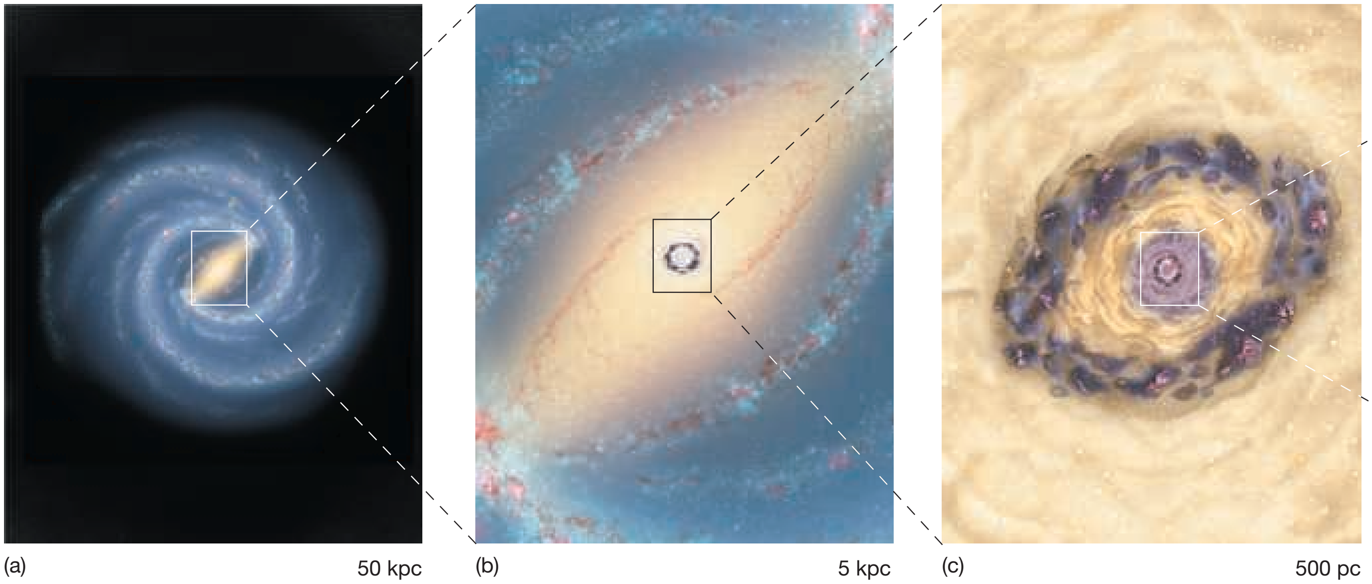


(b)

▲ **FIGURE 14.24 Orbits Near the Galactic Center** (a) This extremely close-up map of the Galactic center (left) was obtained by infrared adaptive optics, resulting in an ultra-high-resolution image of the innermost 0.1 pc of the Milky Way. The inset shows the orbit of the innermost star in the frame, labeled S2, between 1992 and 2003. The solid line shows the best-fitting orbit for S2 around a black hole of 4 million solar masses, located at Sgr A* (marked with a cross). (b) The orbits of several stars near the Galactic center share a common focus—Sgr A*. *(ESO)*

A* cannot be much larger than 10 AU, and it is probably a good deal smaller than that. ∞ *(Sec. 3.4)* This size is consistent with the view that the energy source is a massive black hole. Figure 14.24 is perhaps the strongest evidence to date supporting the black hole picture. It shows a high-resolution infrared image of an 0.04-pc (8000 AU) field near the Galactic center, centered on Sgr A*. Using advanced adaptive-optics techniques on the Keck telescope and the VLT, two teams of researchers from the United States and Europe have created the first-ever diffraction-limited (0.05 resolution) images of the region. ∞ *(Sec. 3.3)*

Remarkably, the image quality is good enough that the *proper motions* of several of the stars—their orbits around the Galactic center—can clearly be seen. The inset shows a series of observations of one of the brightest stars—called S2—over a 10-year period. The motion is consistent with an orbit around a massive object at the location of Sgr A*, in accordance with Newton's laws of motion. ∞ *(Sec. 1.4)* The solid curve on the figure shows the elliptical orbit that best fits the observations. It corresponds to a 15-year orbit with a semimajor axis of 950 AU, corresponding (from Kepler's third law, as modified by Newton) to a

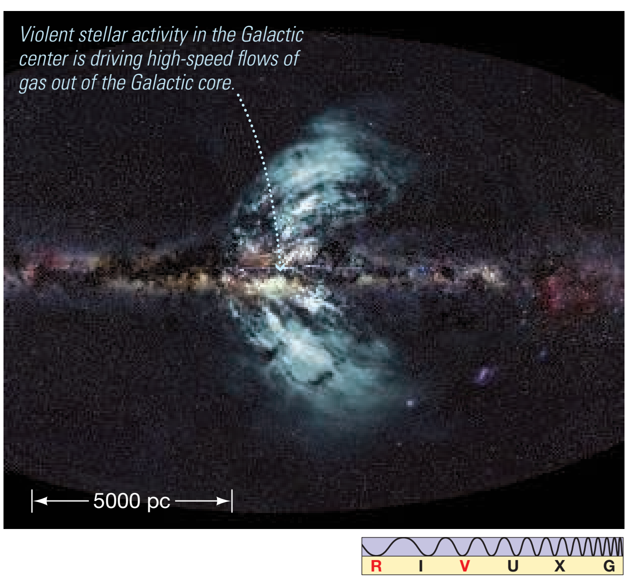


▲ **FIGURE 14.25 Galactic Center Zoom** This series of artist's conceptions of the Galactic center depicts each frame increasing in resolution by a factor of 10. Frame (a) is the same scene as Figure 14.15. Frame (f) is a rendition of a vast whirlpool within the innermost 0.5 parsec of our Galaxy. The data imaged in Figure 14.23 do not closely match these artistic renderings because the Figure 14.23 view is parallel to the Galactic disk—along the line of sight from the Sun to the Galactic center—whereas these six paintings portray a simplified view perpendicular to the disk, while progressively zooming down onto that disk.

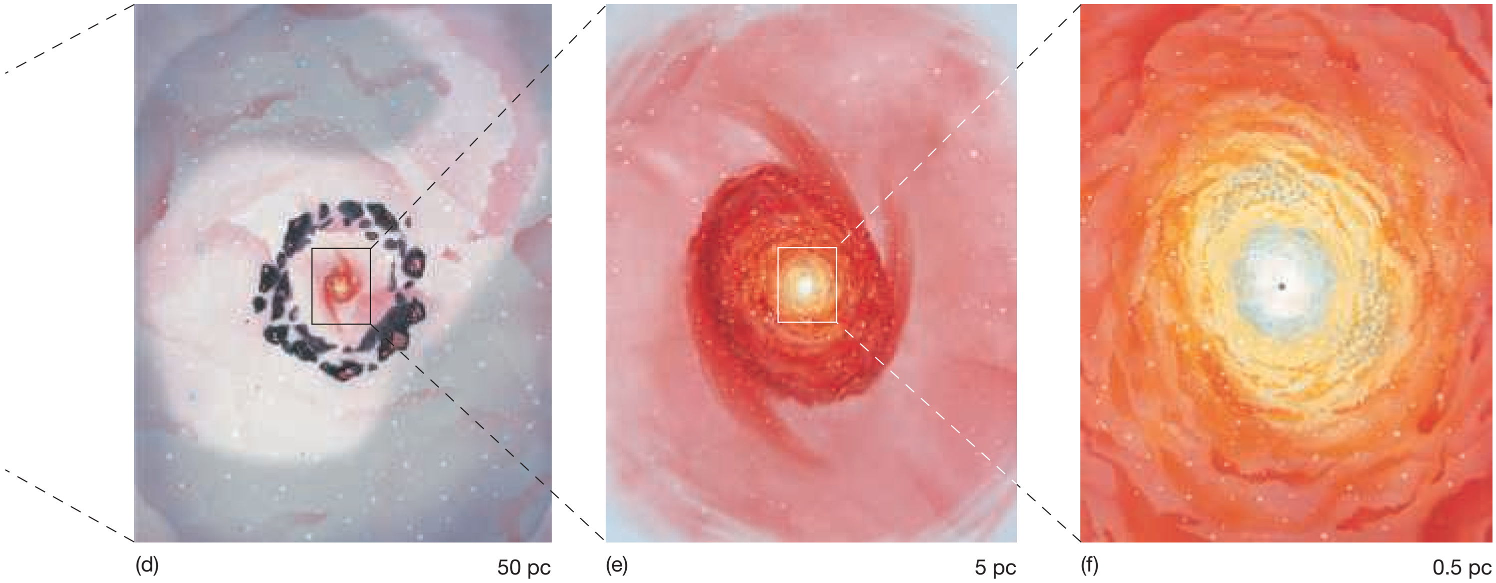
central mass of 4 million solar masses. The small size of the central object is clearly demonstrated by the orbit of another star (S16), whose extremely eccentric orbit brings it within 45 AU of the center. Note that, even with this large mass, if Sgr A* is indeed a genuine black hole, the size of its event horizon is still only 0.08 AU. ∞ *(Sec. 13.5)* Such a small region, 8 kpc away, is currently unresolvable, although radio astronomers are hopeful that improving VLBI techniques will allow them to "see" the event horion and study the surrounding accretion disk within the next decade.

Figure 14.25 places these findings into a simplified perspective—all frames are artist's conceptions, but are based on real data. Each frame is centered on the Galaxy's core, with an increase in resolution of a factor of 10 from one frame to the next. Frame (a) renders the Galaxy's overall shape, as shown in Figure 14.15. This frame measures about 50 kpc across. Frame (b) spans a distance of 5 kpc and is nearly filled by the Galactic bar and the great circular sweep of the innermost spiral arm. Moving in to a 500-pc span, frame (c) depicts the 400-pc ring of gas mentioned earlier and some young dense star clusters, evidence of recent star formation near the Galactic center. The dark blobs represent giant molecular clouds, the pink patches emission nebulae associated with star formation within them.

In frame (d), at 50 pc, a pinkish (thin, warm) region of ionized gas surrounds the reddish (thicker, warmer) heart of the Galaxy. The energy responsible for this vast ionized region comes from frequent supernovae and other violent activity in the Galactic center. The central star cluster (diluted in



◄ **FIGURE 14.26 Galactic Outflow** Radio observations reveal a huge outflow of gas (blue) from the Galactic center, here superimposed on an optical image of the Galactic disk, most likely driven by supernovae in the dense Galactic core.



the painting for clarity) and the surrounding star-forming ring can also be seen. Recent multiwavelength observations reveal that this intense stellar activity has blasted huge (10 kpc long) magnetized jets of high-energy particles out of the Galactic center, roughly perpendicular to the disk (Figure 14.26). The total energy in the jets exceeds that of a typical supernova by about a factor of a million. Astronomers suspect that similar events are occurring at the centers of many other galaxies. Also shown in frame (d) are numerous young dense star clusters, further evidence of recent bursts of star formation near the Galactic center. Frame (e), spanning 5 pc, depicts the ring in more detail as well as the central cluster, along with the tilted, spinning whirlpool of hot (10^4 K) gas surrounding the center of our Galaxy. The innermost part of this gigantic whirlpool is shown in frame (f), in which a swiftly spinning, white-hot disk of gas with temperatures in the millions of kelvins nearly engulfs the central black hole (represented here as a black dot). Two rings of stars, possibly the remains of disrupted star clusters, have also been detected, as roughly sketched in frame (f). The black hole itself, and the stellar orbits shown in Figure 14.24, are far too small to be pictured on this scale.

The last decade has seen an explosion in our knowledge of the innermost few parsecs of our Galaxy, and astronomers are working hard to decipher the clues hidden within its invisible radiation. Still, we are only now beginning to appreciate the full complexity of this strange realm deep in the heart of the Milky Way.

CONCEPT CHECK

What is the most likely explanation of the energetic events observed at the Galactic center?

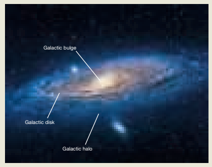
THE BIG QUESTION

How big is the Milky Way? How well do we know the size, shape, and mass of our colossal home in the cosmos? In recent years, astronomers have reexamined our system of stars, gas, and dark matter: Its total mass has been upgraded by nearly a factor of ten, its extended halo might reach halfway to the nearest galaxy, and its dark matter outweighs its normal matter by at least a factor of five. Even so, have we seriously underestimated the scale of this grand system?

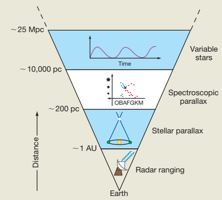
CHAPTER REVIEW

SUMMARY

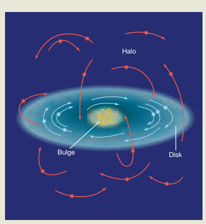
LO1 A **galaxy** (p. 392) is a huge collection of stellar and interstellar matter isolated in space and bound together by its own gravity. Because we live within it, the **Galactic disk** (p. 392) of our **Milky Way Galaxy** (p. 392) appears as a broad band of light across the sky—the Milky Way. Near the center, the Galactic disk thickens into the **Galactic bulge** (p. 392). The disk is surrounded by a roughly spherical **Galactic halo** (p. 392) of old stars and star clusters. Our Galaxy, like many others visible in the sky, is a spiral galaxy. Disk and halo stars differ in their spatial distributions, ages, colors, and orbital motion. The luminous portion of our Galaxy has a diameter of about 30 kpc. In the vicinity of the Sun, the Galactic disk is about 300 pc thick.



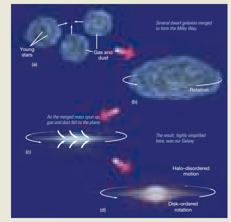
LO2 The halo can be studied using **variable stars** (p. 394), whose luminosity changes with time. Two types of pulsating variable stars of particular importance to astronomers are **RR Lyrae variables** (p. 394) and **Cepheid variables** (p. 394). All RR Lyrae stars have roughly the same luminosity. For Cepheids, the luminosity can be determined using the **period–luminosity relationship** (p. 395). Knowing the luminosity, astronomers apply the inverse-square law to find the distance. The brightest Cepheids can be seen at distances of millions of parsecs, extending the cosmic distance ladder well beyond our own Galaxy. In the early 20th century, Harlow Shapley used RR Lyrae stars to determine the distances to many of the Galaxy's globular clusters and found that they have a roughly spherical distribution in space, but the center of the sphere lies far from the Sun—it is close to the **Galactic center** (p. 396), about 8 kpc away.



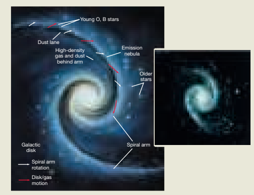
LO3 Stars and gas within the Galactic disk move on roughly circular orbits around the Galactic center. Stars in the halo and bulge move on largely random three-dimensional orbits that pass repeatedly through the disk plane but have no preferred orientation.



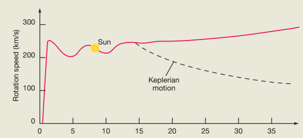
LO4 The halo lacks gas and dust, so no stars are forming there. All halo stars are old. The gas-rich disk is the site of current star formation and contains many young stars. Halo stars appeared early on, before the Galactic disk took shape, when there was still no preferred orientation for their orbits. As the gas and dust formed a rotating disk, stars that formed in the disk inherited its overall spin and so moved on circular orbits in the Galactic plane, as they do today.



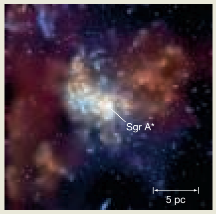
LO5 Radio observations clearly reveal the extent of our Galaxy's **spiral arms** (p. 401), regions of the densest interstellar gas where star formation is taking place. The spirals cannot be "tied" to the disk material, as differential rotation would have wound them up long ago. Instead, they may be **spiral density waves** (p. 402) that move through the disk, triggering star formation as they pass by. Alternatively, the spirals may arise from **self-propagating star formation** (p. 403), when shock waves produced by the formation and evolution of one generation of stars trigger the formation of the next.



LO6 The Galactic **rotation curve** (p. 406) plots the orbital speed of matter in the disk against distance from the Galactic center. By applying Newton's laws of motion, astronomers can determine the mass of the Galaxy. The Galactic mass continues to increase beyond the radius defined by the globular clusters and the spiral structure we observe, indicating that our Galaxy has an invisible **dark halo** (p. 406). The **dark matter** (p. 406) making up this dark halo is of unknown composition. Candidates include low-mass stars and exotic subatomic particles. Recent attempts to detect stellar dark matter have used the fact that a faint foreground object can occasionally pass in front of a more distant star, deflecting the star's light and causing its apparent brightness to increase temporarily. This deflection is called **gravitational lensing** (p. 407).



LO7 Astronomers working at infrared and radio wavelengths have uncovered evidence for energetic activity within a few parsecs of the Galactic center. The leading explanation is that a black hole roughly 4 million times more massive than the Sun resides there. The hole lies at the center of a dense star cluster containing millions of stars, which is in turn surrounded by a star-forming disk of molecular gas. The observed activity is thought to be powered by accretion onto the black hole, as well as by supernova explosions in the cluster surrounding it.



Problems labeled POS explore the process of science. VIS problems focus on reading and interpreting visual information. LO connects to the introduction's numbered Learning Outcomes.

REVIEW AND DISCUSSION

1. LO1 POS What do globular clusters tell us about our Galaxy and our place within it?
2. How are Cepheid variables used in determining distances?
3. How far away can we use Cepheids to measure distance?
4. LO2 What important discoveries were made early in this century using RR Lyrae variables?
5. Why can't optical astronomers easily study the center of our Galaxy?
6. Why are radio studies often more useful in the study of Galactic structure than observations made in visible light?
7. LO3 Contrast the motions of disk and halo stars.
8. LO5 POS Explain why Galactic spiral arms are thought to be regions of recent and ongoing star formation.
9. Describe what happens to interstellar gas as it passes through a spiral density wave.
10. What is self-propagating star formation?
11. LO4 What do halo stars tell us about the history of our Galaxy?
12. What does a galaxy's rotation curve tell us about its total mass?
13. LO6 POS What evidence is there for dark matter in the Galaxy?
14. Describe some candidates for Galactic dark matter.
15. LO7 POS Why do astronomers think that a supermassive black hole lies at the center of the Milky Way Galaxy?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. Herschel's attempt to map the Milky Way by counting stars led to an inaccurate estimate of the Galaxy's size because he was unaware of absorption by interstellar dust. (T/F)
2. Cepheid variables can be used to determine the distances to the nearest galaxies. (T/F)
3. Globular clusters trace out the structure of the Galactic disk. (T/F)
4. The Galactic halo contains as much gas and dust as the disk. (T/F)
5. The Galactic disk contains only old stars. (T/F)
6. Stars and gas in the Galactic disk move in roughly circular orbits around the Galactic center. (T/F)
7. We can use 21-cm radiation to study molecular clouds. (T/F)
8. The most likely explanation of the high-speed motion of stars and gas near the Galactic center is that they are orbiting a supermassive black hole. (T/F)
9. In the Milky Way Galaxy, our Sun is located (a) near the Galactic center; (b) about halfway out from the center; (c) at the outer edge; (d) in the halo.
10. A telescope searching for newly formed stars would make the most discoveries if it were pointed (a) directly away from the Galactic center; (b) perpendicular to the Galactic disk; (c) within a spiral arm; (d) between spiral arms.
11. The first stars that formed in the Milky Way now (a) have chaotic orbits; (b) orbit in the Galactic plane; (c) orbit near the Galactic center; (d) orbit in the same direction as the Milky Way spins.
12. Stars in the outermost regions of the Milky Way Galaxy (a) are youngest; (b) orbit faster than astronomers would expect based on the Galactic mass we can see; (c) are more likely to explode as supernovae; (d) are more luminous than other stars.

13. Most of the mass of the Milky Way exists in the form of (a) stars; (b) gas; (c) dust; (d) dark matter.
14. VIS In Figure 14.6 (Period–Luminosity Relationship), a Cepheid variable star with luminosity 1000 times that of the Sun has a pulsation period of roughly (a) 1 day; (b) 3 days; (c) 10 days; (d) 50 days.
15. VIS Figure 14.20 (Galaxy Rotation Curve) tells us that (a) the Galaxy rotates like a solid body; (b) far from the center, the Galaxy rotates more slowly than we would expect based on the light we see; (c) far from the center, the Galaxy rotates more rapidly than we would expect based on the light we see; (d) there is no matter beyond about 15 kpc from the Galactic center.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ At one time some astronomers claimed that the Andromeda "nebula" (Figure 14.2a) was a star-forming region lying within our Galaxy. Calculate the angular diameter of a prestellar nebula of radius 100 AU, lying 100 pc from Earth. How close to Earth would the nebula have to lie for it to have the same angular diameter (roughly 6°) as Andromeda?
2. ■ What is the greatest distance at which an RR Lyrae star of absolute magnitude 0 could be seen by a telescope capable of detecting objects as faint as 20th magnitude? ∞ ***(Sec. 10.2)***
3. ■ A typical Cepheid variable is 100 times brighter than a typical RR Lyrae star. On average, how much farther away than RR Lyrae stars can Cepheids be used as distance-measuring tools?
4. ■■ An astronomer using *HST* can just see a star with solar luminosity at a distance of 100,000 pc. The brightest Cepheids are 30,000 times more luminous than the Sun. If the Sun's absolute magnitude is 5, calculate the absolute magnitudes of these bright Cepheids. Neglecting interstellar absorption, how far away can *HST* see them?
5. ■■ Calculate the proper motion (in arc seconds per year) of a globular cluster with a transverse velocity (relative to the Sun) of 200 km/s and a distance of 3 kpc. Might this motion be measurable? ∞ ***(Sec. 10.1)***
6. ■■ Calculate the total mass of the Galaxy lying within 20 kpc of the Galactic center if the rotation speed at that radius is 240 km/s.
7. ■■■ Using the data presented in Figure 14.20, calculate how long it takes the Sun to "lap" stars orbiting 15 kpc from the Galactic center.
8. ■ A two-arm spiral density wave is moving through the Galactic disk. At the 8-kpc radius of the Sun's orbit around the Galactic center, the wave's speed is 120 km/s, and the Galactic rotation speed is 220 km/s. How many times has the Sun passed through a spiral arm since the Sun formed 4.6 billion years ago?
9. ■■ Given the data in the previous question and the fact that O-type stars live at most 10 million years before exploding as supernovae, calculate the maximum distance at which an O-type star (orbiting at the Sun's distance from the Galactic center) can be found from the density wave in which it formed.
10. ■■■ Material at an angular distance of 0.2 from the Galactic center is observed to have an orbital speed of 1200 km/s. If the Sun's distance to the Galactic center is 8 kpc and the material's orbit is circular and is seen edge-on, calculate the radius of the orbit and the mass of the object around which the material is orbiting.

ACTIVITIES

Collaborative

1. Construct your own electronic version of the Messier catalog, listing the names, types, and coordinates of all 110 Messier objects. (You should be able to find all the needed information on the Web, although you may end up combining information from more than one source.) Use a spreadsheet to plot the celestial coordinates—right ascension and declination—of all objects. ***(Sec. 0.1)*** Color-code the objects to distinguish among emission nebulae, young star clusters, older open star clusters, globular clusters, and galaxies. What do you notice about the distributions of these objects on the sky? It might help to sketch the approximate location of the Milky Way (more research!) on the plot. Why are the young objects mainly found in the plane of the Milky Way. What about the globular clusters? Why do you think the galaxies apparently avoid the Galactic plane? If you have time, add deep-sky objects from other catalogs to your plot.

Individual

1. If you are far from city lights, look for a hazy band of light arching across the sky. This is our edgewise view of the Milky Way Galaxy. The Galactic center is located in the direction of the constellation Sagittarius, highest in the sky in summer, but visible from spring through fall. Look at the band making up the Milky Way and sketch what you see. Look for dark regions and faint fuzzy spots in the Milky Way; note their positions on your sketch. Add the major constellations for reference. Compare your sketch with a map of the Milky Way in a star atlas. Can you identify the dark regions and faint fuzzy spots?

1. Observe the Andromeda galaxy, M31. It's the most distant object visible to the naked eye, but don't expect to see anything like Figure 14.2(a)! To the unaided eye, from all but the darkest sites, only its nucleus will be visible, looking like a slightly fuzzy star. To locate M31, find Polaris, the pole star, and the constellations Cassiopeia and Andromeda. Follow a line from Polaris through the second "V" in the "W" of Cassiopeia, and continue south. That line will pass through M31 before you reach the northern arc of stars in Andromeda. Use binoculars or a wide-angle eyepiece to view the galaxy and its disk. Switch to higher magnification to view the nucleus and the small satellite galaxies M32, just to its south, and M110, to the northwest.

15

Normal and Active Galaxies

Building Blocks of the Universe

As our field of view expands to truly cosmic scales, the focus of our studies shifts dramatically. Planets become inconsequential, stars themselves mere points of hydrogen consumption. Now entire galaxies become the "atoms" from which the universe is built—distant realms completely unknown to scientists just a century ago. We know of literally millions of galaxies beyond our own. Most are smaller than the Milky Way, some comparable in size, a few much larger. Many are sites of explosive events far more energetic than anything ever witnessed in our own Galaxy. All are vast, gravitationally bound assemblages of stars, gas, dust, dark matter, and radiation separated from us by almost incomprehensibly large distances. The light we receive tonight from the most distant galaxies was emitted long before Earth existed. By studying the properties of galaxies and the violence that ensues when they collide, we gain insight into the history of our Galaxy and the universe in which we live.

THE BIG PICTURE

Light collected tonight from the most distant galaxies was emitted by those objects long before Earth even formed. Racing for billions of years across the darkened realms of the cosmos, a minute fraction of their radiation is now intercepted by our telescopes and spacecraft. Captured in the many images of this book, that radiation tells us not only about the properties of faraway galaxies, but also about the history of our Galaxy and the universe in which we live.

◂ The giant elliptical galaxy M87 lies some 17 megaparsecs from Earth, at the center of the Virgo galaxy cluster. Its full diameter is about 30 kpc—not much different from the Milky Way—although only the innermost 5 kpc is shown here. However, with several trillion stars, more than 10,000 globular clusters, and a 4 billion-solar-mass black hole at its center, M87 dwarfs our Galaxy in all other respects. Accretion of stars onto the central supermassive black hole has created a high-speed jet of matter leaving the galaxy's central nucleus at nearly the speed of light. The jet, nucleus, and surrounding galaxy can all be seen in this visible-light *Hubble Space Telescope* image. *(NASA/ESA)*

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** List the basic properties and main types of normal galaxies.
- **LO2** Explain the distance-measurement techniques that enable astronomers to map the universe beyond the Milky Way.
- **LO3** Describe how galaxies are observed to clump into clusters.
- **LO4** State Hubble's law, and explain how it is used to determine distances to the most remote objects in the observable universe.
- **LO5** Specify how active galaxies differ from normal galaxies, and describe some of their basic features.
- **LO6** Describe some types of active galaxies.
- **LO7** Explain what drives the central engine thought to power all active galaxies.

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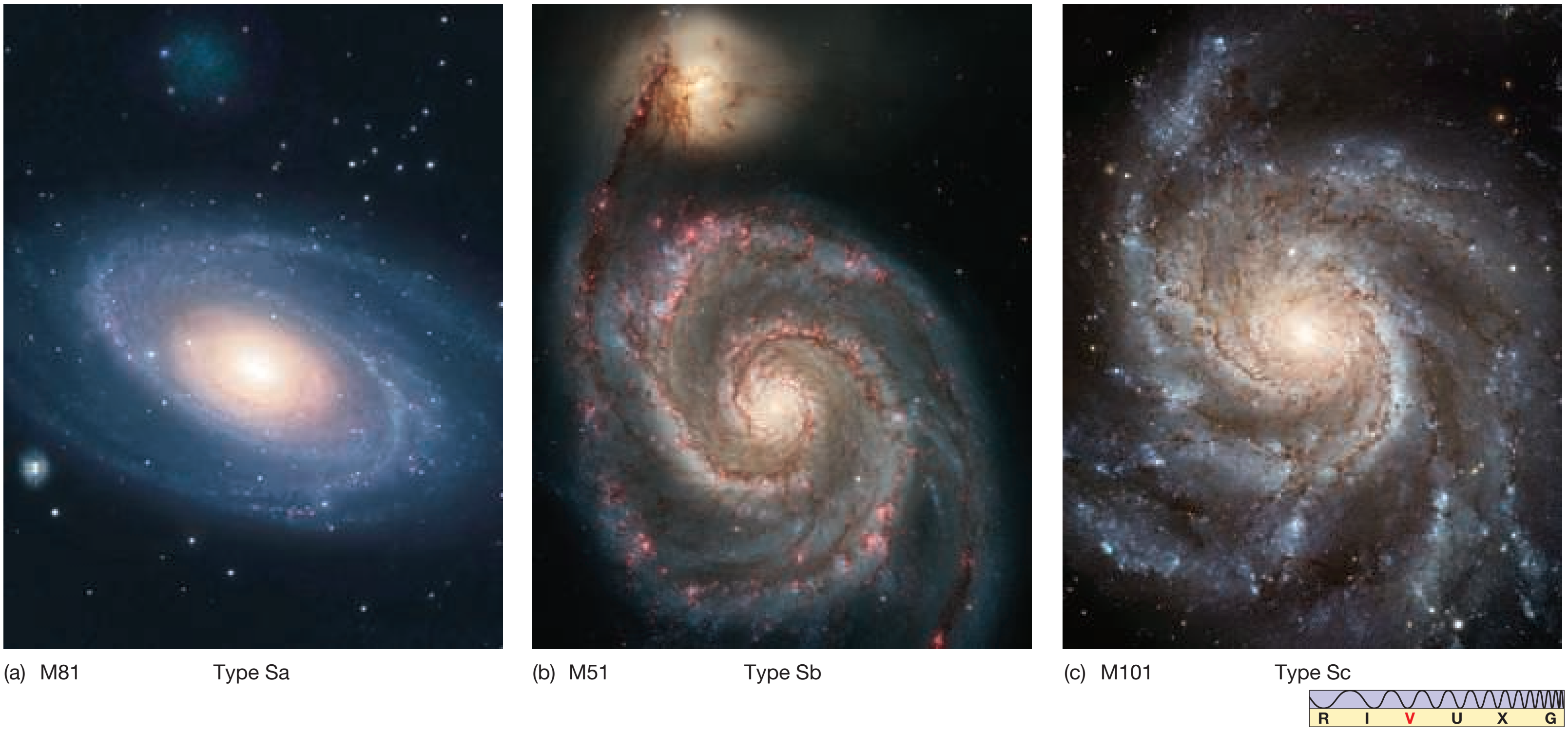
15.1 Hubble's Galaxy Classification

Figure 15.1 shows a vast expanse of space lying about 150 million parsecs from Earth. Almost every patch or point of light in this figure is a galaxy—several hundred can be seen in just this one photograph. Images of galaxies look distinctly nonstellar. They have fuzzy edges, and many are quite elongated—not at all like the sharp, point-like images normally associated with stars. Some of the blobs of light in Figure 15.1 are spiral galaxies like the Milky Way Galaxy and Andromeda. Others, however, are definitely not spirals—no disks or spiral arms can be seen. Even when we take into account their different orientations in space, galaxies do *not* all look the same.

American astronomer Edwin Hubble was the first to categorize galaxies in a comprehensive way. Working with the then recently completed 2.5-m optical telescope on Mount Wilson in California in 1924, he classified the galaxies he saw into four basic types—*spirals, barred spirals, ellipticals,* and *irregulars*—solely on the basis of their visual appearance. Many modifications and refinements have been incorporated over the years, but the basic **Hubble classification scheme** is still widely used today.

▼ **FIGURE 15.1 Galaxy Cluster** This is Abell S0740, a collection of many galaxies, each consisting of hundreds of billions of stars. Although dominated by the large elliptical galaxy at the upper right, the system contains galaxies of many different types. The spiral galaxy at lower left is comparable in size to the Milky Way. *(NASA)*



▲ **FIGURE 15.2 Spiral Galaxy Shapes** Variation in shape among spiral galaxies. As we progress from type Sa to Sb to Sc, the bulges become smaller, while the spiral arms tend to become less tightly wound. *(R. Gendler; NASA)*

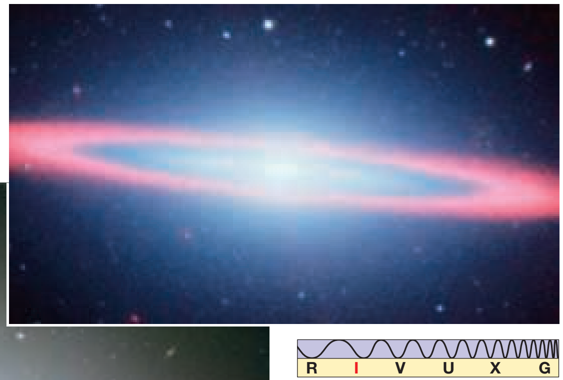
Spirals

We saw several examples of **spiral galaxies** in Chapter 14 previously—for example, our own Milky Way Galaxy and our neighbor Andromeda. All galaxies of this type contain a flattened galactic disk in which spiral arms are found, a central galactic bulge with a dense nucleus, and an extended halo of faint, old stars. ***(Sec. 14.3)*** The stellar density (that is, the number of stars per unit volume) is greatest in the galactic nucleus, at the center of the bulge. ∞ ***(Sec. 14.7)***

In Hubble's scheme, a spiral galaxy is denoted by the letter S and classified as type a, b, or c according to the size of its central bulge: Type Sa galaxies have the largest bulges, type Sc the smallest (Figure 15.2). The tightness of the spiral pattern is quite well correlated with the size of the bulge (although the correspondence is not perfect). Type Sa spiral galaxies tend to have tightly wrapped, almost circular, spiral arms. Type Sb galaxies typically have more open spiral arms, while type Sc spirals often have loose, poorly defined spiral structure. The arms also tend to become more "knotty," or clumped, in appearance as the spiral pattern becomes more open. Based on all available evidence, the Milky Way is a barred spiral galaxy, most likely of type SBb. ∞ ***(Sec. 14.5)***

The bulges and halos of spiral galaxies contain large numbers of reddish old stars and globular clusters, similar to those observed in our own Galaxy and in Andromeda. ∞ ***(Sec. 14.1)*** Most of the light from spirals, however, comes from younger A- through G-type stars in the disk, giving these galaxies an overall whitish glow. As in the Milky Way, the disks of typical spiral galaxies are rich in gas and dust. The 21-cm radio radiation emitted by spirals betrays the presence of interstellar gas, and obscuring dust lanes are clearly visible in many systems (see Figures 15.2b and c). Stars are forming within the spiral arms, which contain numerous emission nebulae and newly formed O- and B-type stars. ∞ ***(Sec. 14.5)*** The arms appear bluish because of the bright blue O- and B-type stars there. Type Sc galaxies contain the most interstellar gas and dust, Sa galaxies the least.

Most spirals are not seen face-on as in Figure 15.2. Many are tilted with respect to our line of sight, making their spiral structure hard to discern. However, we do not



▲ **FIGURE 15.3 Sombrero Galaxy** The Sombrero Galaxy (M104), a spiral system seen edge-on, has a dark band composed of interstellar gas and dust. The large size of this galaxy's central bulge marks it as type Sa, even though its spiral arms cannot be seen from our perspective. The inset shows this galaxy in the infrared part of the spectrum, highlighting its dust content in false-colored pink. *(NASA)*

need to see spiral arms to classify a galaxy as a spiral. The presence of the disk, with its gas, dust, and newborn stars, is sufficient. For example, the galaxy shown in Figure 15.3 is classified as a spiral because of the clear line of obscuring dust seen along its midplane. That dust is evident most clearly in the inset infrared image, which was acquired by the *Spitzer Space Telescope*.

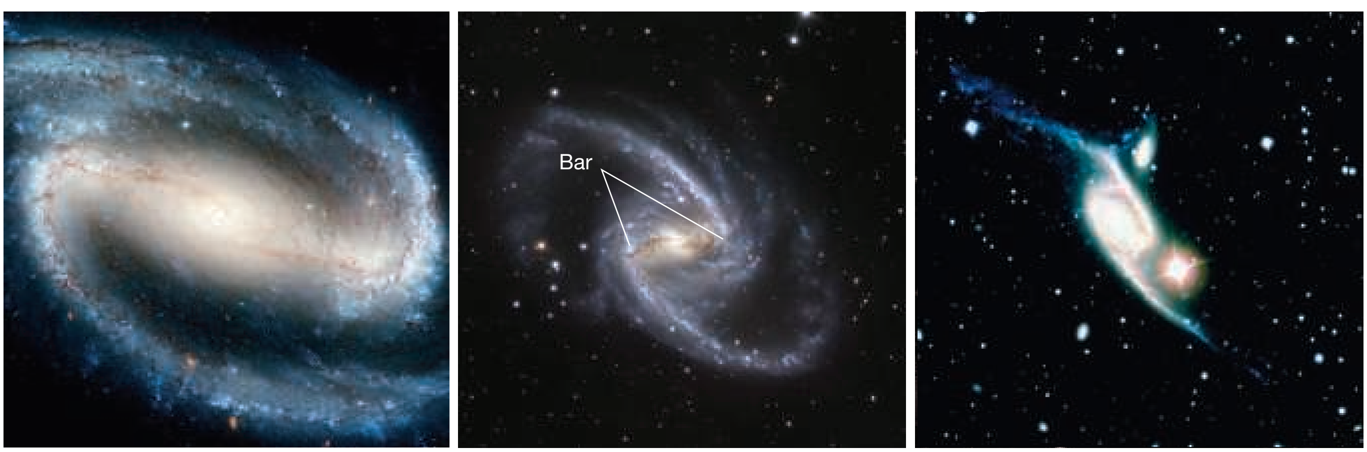
A variation of the spiral category in Hubble's classification scheme is the **barred-spiral galaxy**. Barred spirals differ from ordinary spirals mainly by the presence of an elongated "bar" of stellar and interstellar matter passing through the center and extending beyond the bulge, into the disk. The spiral arms project from near the ends of the bar rather than from the bulge (as they do in normal spirals). Barred spirals are designated by the letters SB and are subdivided, like the ordinary spirals, into categories SBa, SBb, and SBc, depending on the size of the bulge. Again like ordinary spirals, the tightness of the spiral pattern is correlated with bulge size. Figure 15.4 shows the variation among barred-spiral galaxies. In the case of the SBc category, it is often hard to tell where the bar ends and the spiral arms begin.

Ellipticals

Unlike the spirals, **elliptical galaxies** have no spiral arms and, in most cases, no obvious galactic disk—in fact, other than a dense central nucleus, they often exhibit little internal structure of any kind. As with spirals, the stellar density increases sharply in the nucleus. Denoted by the letter E, these systems are subdivided according to how elliptical they appear on the sky. The most circular are designated E0, slightly flattened systems are labeled E1, and so on, all the way to the most elongated ellipticals, of type E7 (Figure 15.5).

Note that an elliptical galaxy's Hubble type depends both on its intrinsic three-dimensional shape *and* on its orientation relative to the line of sight. A spherical galaxy, a cigar-shaped galaxy seen end-on, and a disk-shaped galaxy seen face-on, would all appear to be circular on the sky and be classified as E0. It can be difficult to decipher a galaxy's true shape solely from its visual appearance.

▼ **FIGURE 15.4 Barred-Spiral Galaxy Shapes** Variation in shape among barred-spiral galaxies from SBa to SBc is similar to that for the spirals in Figure 15.2, except that here the spiral arms begin at either end of a bar through the galactic center. In frame (c), the bright star is a foreground object in our own Galaxy. *(NASA; ESO; Gemini)*



(a) NGC 1300 Type SBa

(b) NGC 1365 Type SBb

(c) NGC 6872 Type SBc

▶ **FIGURE 15.5 Elliptical Galaxy Shapes** (a) The E1 elliptical galaxy IC 2006 is nearly circular in appearance. (b) NGC 1132 is slightly more elongated and classified as E4. Both galaxies lack spiral structure, and neither shows evidence of interstellar dust or gas, although each has an extensive X-ray halo of hot gas that extends far beyond the visible portion of the galaxy. (c) M110 is a dwarf elliptical companion to the much larger Andromeda galaxy. *(NASA/ESA; NOAO)*

(a) IC 2006 Type E1

(b) NGC 1132 Type E4

(c) M110 Type E5

There is a large range in both the size and the number of stars contained in elliptical galaxies. The largest elliptical galaxies are much larger than our Milky Way Galaxy. These *giant ellipticals* can range up to hundreds of thousands of megaparsecs across and contain tens of trillions of stars (see the chapter-opening image on p. 418 of the E0 giant elliptical M87). At the other extreme, *dwarf ellipticals* may be as small as 1 kpc in diameter and contain fewer than a million stars. Their many differences suggest to astronomers that giant and dwarf ellipticals represent distinct galaxy classes, with quite dissimilar formation histories and stellar content. The dwarfs are by far the most common type of ellipticals, outnumbering their brighter counterparts by about 10 to 1. However, most of the *mass* that exists in the form of elliptical galaxies is contained in the larger systems.

Lack of spiral arms is not the only difference between spirals and ellipticals. Most ellipticals also contain little or no cool gas and dust and display no evidence of young stars or ongoing star formation. Like the halo of our Galaxy, ellipticals are composed mostly of old, reddish, low-mass stars. Again like the halo of our Galaxy, the orbits of stars in ellipticals are disordered, exhibiting little or no overall rotation; objects move in all directions, not in regular, circular paths as in our Galaxy's disk. Ellipticals differ from our Galaxy's halo in at least one important respect, however: X-ray observations reveal large amounts of very *hot* (several million kelvin) interstellar gas distributed throughout their interiors, often extending well beyond the visible portions of the galaxies.

Some giant ellipticals are exceptions to many of these general statements, as they contain disks of gas and dust in which stars are forming. Astronomers think that these systems may be the results of mergers between gas-rich galaxies (see Chapter 16). Indeed, galactic collisions may have played an important role in determining the appearance of many of the systems we observe today.

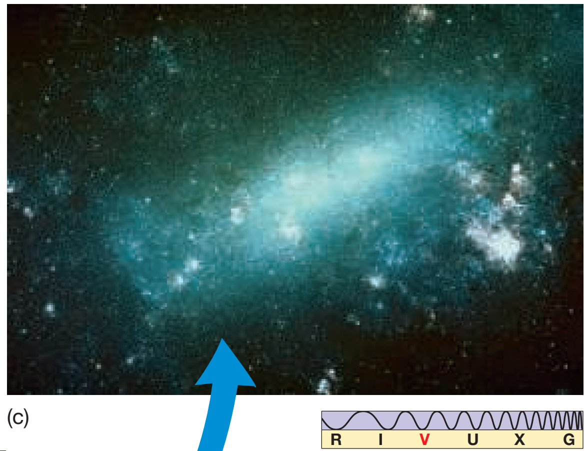
Intermediate between the E7 ellipticals and the Sa spirals in the Hubble classification is a class of galaxies that show evidence of a thin disk and a flattened bulge yet contain neither loose gas nor spiral arms. Two such objects are shown in Figure 15.6. These galaxies are called **S0 galaxies** (S-zero) if no bar is evident and **SB0 galaxies** if a bar is present. They are also known as *lenticular* galaxies, because of their lens-shaped appearance. They look a little like spirals whose dust and gas have been stripped away, leaving behind just a stellar disk. Observations in recent years have shown that many normal elliptical galaxies have faint disks within them, like the S0 galaxies. As with the S0s, the origin of these disks is uncertain, but some researchers suspect that S0s and ellipticals may be closely related.

(a) IC 335 Type S0

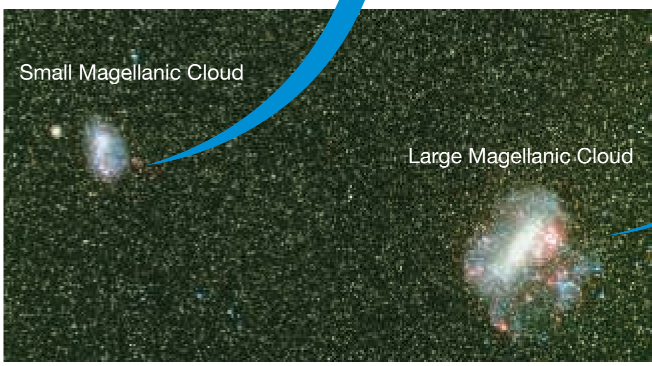
(b) NGC 4435 Type SB0

◀ **FIGURE 15.6 S0 Galaxies** (a) S0 (or lenticular) galaxies contain a disk and a bulge, but no interstellar gas and no spiral arms. Their properties are intermediate between E7 ellipticals and Sa spirals. (b) SB0 galaxies are similar to S0 galaxies, except for a bar of stellar material extending beyond the central bulge. *(Palomar/Caltech)*

(b)



(c)



(a)

▲ **FIGURE 15.7 Magellanic Clouds** The Magellanic Clouds are prominent features of the night sky in the Southern Hemisphere. Named for the 16th-century Portuguese explorer Ferdinand Magellan, whose around-the-world expedition first brought word of these fuzzy patches of light to Europe, these dwarf irregular galaxies orbit our Galaxy and accompany it on its trek through the cosmos. (a) The Clouds' relationship to one another in the southern sky reveals both the Small (b) and the Large (c) Clouds to have distorted, irregular shapes. *(Mount Stromlo & Siding Spring Observatories)*

Irregulars

The final galaxy class identified by Hubble is a catch-all category—**irregular galaxies**—so named because their visual appearance excludes them from the other categories just discussed. Irregulars tend to be rich in interstellar matter and young, blue stars, but they lack any regular structure, such as well-defined spiral arms or central bulges. Irregular galaxies tend to be smaller than spirals but somewhat larger than dwarf ellipticals. They typically contain between 10^8 and 10^{10} stars. The smallest are called *dwarf irregulars*. As with elliptical galaxies, the dwarf type is the most common. Dwarf ellipticals and dwarf irregulars occur in approximately equal numbers and together make up the vast majority of galaxies in the universe. They are often found close to a larger "parent" galaxy.

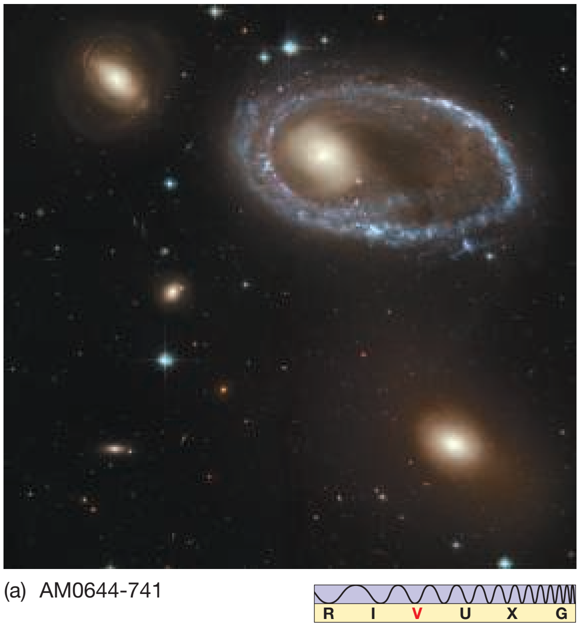
Irregular galaxies are divided into two subclasses—Irr I and Irr II. The Irr I galaxies often look like misshapen spirals. Figure 15.7 shows the **Magellanic Clouds**, a famous pair of Irr I galaxies that orbit the Milky Way Galaxy. They are shown to proper scale in Figure 14.15. Studies of Cepheid variables within the Clouds show them to be approximately 50 kpc from the center of our Galaxy. ∞ *(Sec. 14.2)* The Large Cloud contains about 6 billion solar masses of material and is a few kiloparsecs across. Both Magellanic Clouds contain lots of gas, dust, and blue stars (as well as the well-documented supernova discussed in *Discovery 12-1*), indicating ongoing star formation. Both also contain many old stars and several old globular clusters, so we know that star formation has been taking place there for a very long time.

The much rarer Irr II galaxies (Figure 15.8), in addition to their irregular shapes, have other peculiarities, often exhibiting a distinctly explosive or filamentary appearance. Their appearance once led astronomers to suspect that violent events had occurred within them. However, it now seems more likely that in some (but probably not all) cases, we are seeing the result of a close encounter or collision between two previously "normal" systems.

The Hubble Sequence

Table 15.1 summarizes the basic characteristics of the various galaxy types. When he first developed his classification scheme, Hubble arranged the galaxy types into the "tuning fork" diagram shown in Figure 15.9. The variation in galaxy types across the diagram, from ellipticals to spirals to irregulars, is often referred to as the **Hubble sequence.**

Hubble's primary aim in creating this diagram was to indicate similarities in appearance among galaxies, but he also regarded the tuning fork as an evolutionary sequence from left to right, with E0 ellipticals evolving into flatter ellipticals and S0 systems that ultimately formed disks and spiral arms. Indeed, Hubble's terminology referring to ellipticals as "early-type" galaxies and spirals as "late-type" is still widely used today. But as far as modern astronomers can tell, there is *no* evolutionary connection of this sort along the Hubble sequence. Isolated



(a) AM0644-741

(b) NGC 1569

▲ **FIGURE 15.8 Irregular Galaxy Shapes** (a) The strangely shaped galaxy AM0644-741 is probably plunging headlong into a group of several other galaxies (two of them shown here), causing huge rearrangements of its stars, gas, and dust. (b) The galaxy NGC 1569 seems to show an explosive appearance, probably the result of a recent galaxywide burst of star formation. *(NASA)*

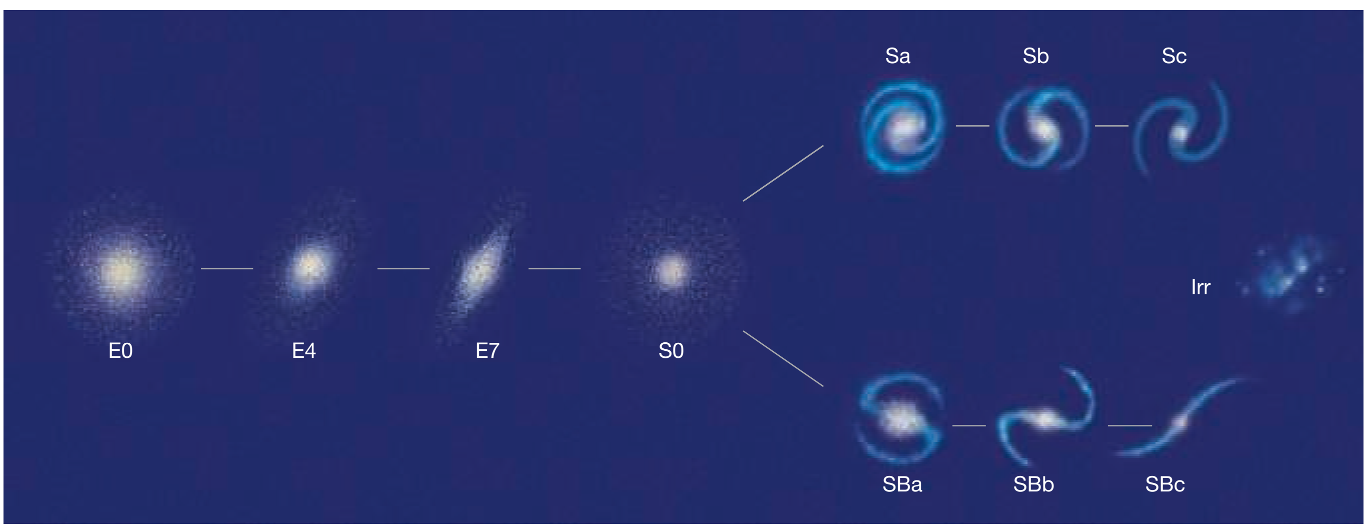
normal galaxies do *not* evolve from one type to another. Spirals are not ellipticals with arms, nor are ellipticals spirals that have somehow shed their star-forming disks. In short, astronomers know of no simple parent–child relationship among Hubble types.

However, the key word here is *isolated*. As we will see, there is now strong observational evidence indicating that collisions and tidal interactions *between* galaxies are commonplace, and these may be the main physical processes driving galaxy evolution. We will return to this important subject in Chapter 16.

MA ANIMATION/VIDEO
The Evolution of Galaxies

CONCEPT CHECK

In what ways are large spirals such as the Milky Way and Andromeda not representative of galaxies as a whole?



▲ **FIGURE 15.9 Galactic "Tuning Fork"** The placement of the four basic types of galaxies—ellipticals, spirals, barred spirals, and irregulars—in Hubble's "tuning-fork" diagram is suggestive, but this galaxy classification scheme has no known physical meaning.

TABLE 15.1 Basic Galaxy Properties by Type

	Spiral/Barred Spiral (S/SB)	Elliptical (E)[1]	Irregular (Irr)
Shape and structural properties	Highly flattened disk of stars and gas containing spiral arms and thickening to central bulge. SB galaxies have an elongated central "bar" of stars and gas.	No disk. Stars smoothly distributed through an ellipsoidal volume. No obvious substructure other than a dense central nucleus.	No obvious structure. Irr II galaxies often have "explosive" appearance.
Stellar content	Disks contain both young and old stars; halos consist of old stars only.	Contain old stars only.	Contain both young and old stars.
Gas and dust	Disks contain substantial amounts of gas and dust; halos contain little of either.	Contain hot X-ray-emitting gas, little or no cool gas and dust.	Very abundant in gas and dust.
Star formation	Ongoing star formation in spiral arms.	No significant star formation during the last 10 billion years.	Vigorous ongoing star formation.
Stellar motion	Gas and stars in disk move in circular orbits around the galactic center; halo stars have random orbits in three dimensions.	Stars have random orbits in three dimensions.	Stars and gas have very irregular orbits.

[1]As noted in the text, some giant ellipticals appear to be the result of mergers between gas-rich galaxies and are exceptions to many of the statements listed here.

15.2 The Distribution of Galaxies in Space

Now that we have seen some of their basic properties, let us ask how galaxies are spread throughout the universe beyond the Milky Way. Galaxies are not distributed uniformly in space. Rather, they tend to clump into still larger agglomerations of matter. As always in astronomy, our understanding hinges on knowing how far away an object lies. We therefore begin by looking more closely at the means used by astronomers to measure distances to galaxies.

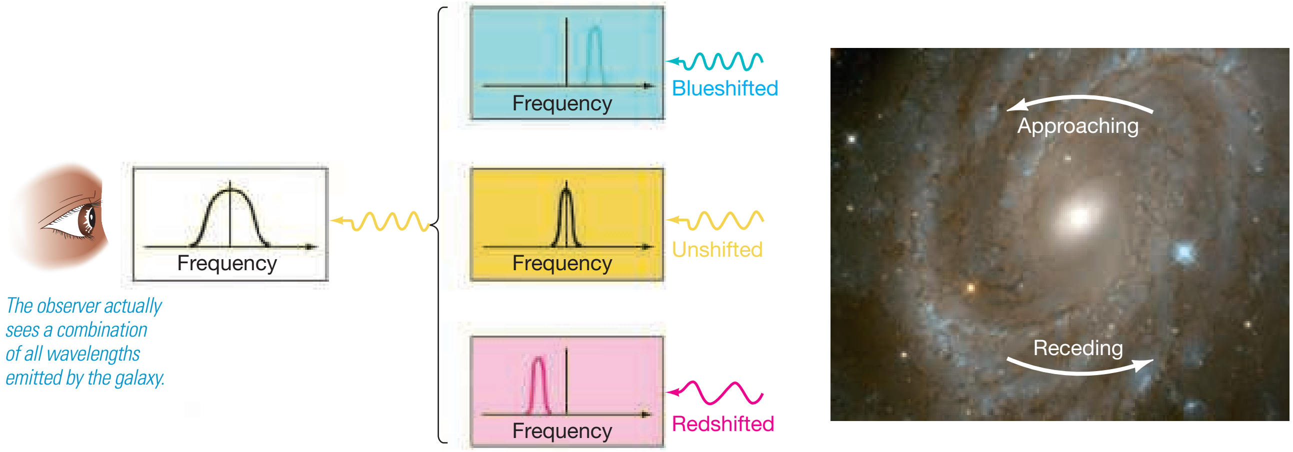
Extending the Distance Scale

Astronomers estimate that some 40 billion galaxies brighter than our own exist in the observable universe. Some reside close enough for the Cepheid variable technique to work—astronomers have detected and measured the periods of Cepheids in galaxies as far away as 25 Mpc. ∞ *(Sec. 14.2)* However, some galaxies contain no Cepheid stars (can you think of some reasons why this might be?), and in any case most known galaxies lie much farther away than 25 Mpc. Cepheid variables in very distant galaxies simply cannot be observed well enough, even through the world's most sensitive telescopes, to allow us to measure their apparent brightness and periods. To extend our distance-measurement ladder, we must find some new object to study.

One way in which researchers have tackled this problem is by using **standard candles**—bright, easily recognizable astronomical objects whose luminosities are confidently known. The basic idea is very simple. Once an object is identified as a standard candle—by its appearance or by the shape of its light curve, say—its luminosity can be estimated. Comparison of the luminosity with the apparent brightness then gives the object's distance, and hence the distance, to the galaxy in which it resides. ∞ *(Sec. 10.2)* Note that, apart from the way in which the luminosity is determined, the Cepheid variable technique relies on identical reasoning—the measured period tells us the luminosity, and the inverse-square law then tells us the distance.

PROCESS OF SCIENCE CHECK

What are some of the problems in measuring accurately the distances to faraway galaxies?



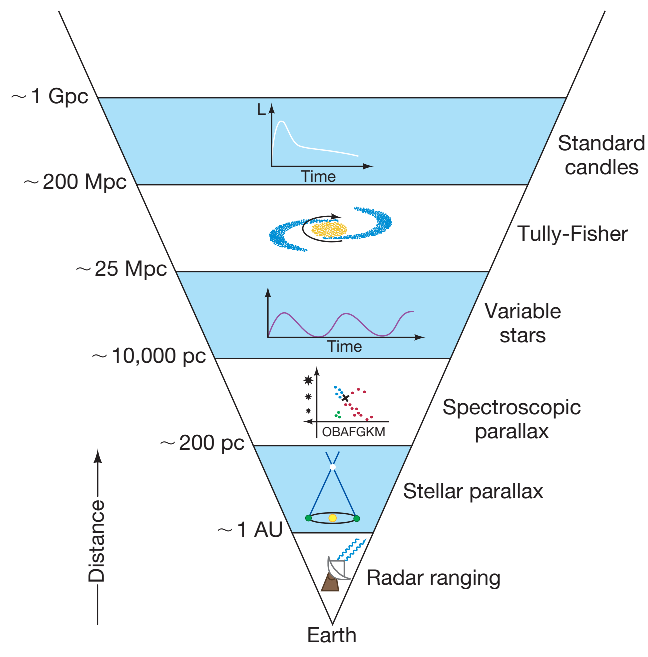
▲ **FIGURE 15.10 Galaxy Rotation** A galaxy's rotation causes some of the radiation it emits to be blueshifted and some redshifted. From a distance, when all the radiation from the galaxy is combined into a single beam and analyzed spectroscopically, the redshifted and blueshifted components produce a broadening of the galaxy's spectral lines. The amount of broadening is a direct measure of the rotation speed of the galaxy, such as NGC 4603 shown here. *(NASA)*

To be most useful, a standard candle must (1) have a well-defined luminosity so that the uncertainty in estimating its brightness is small and (2) be bright enough to be seen at great distances. Currently, Cepheid variable stars are usable for distance measurement "only" out to about 25 Mpc. In recent years, planetary nebulae and Type I supernovae have proved particularly reliable as standard candles. ∞ *(Secs. 12.3, 12.5)* The latter have remarkably consistent peak luminosities and are bright enough to be identified and measured out to distances of more than a gigaparsec (1000 Mpc).

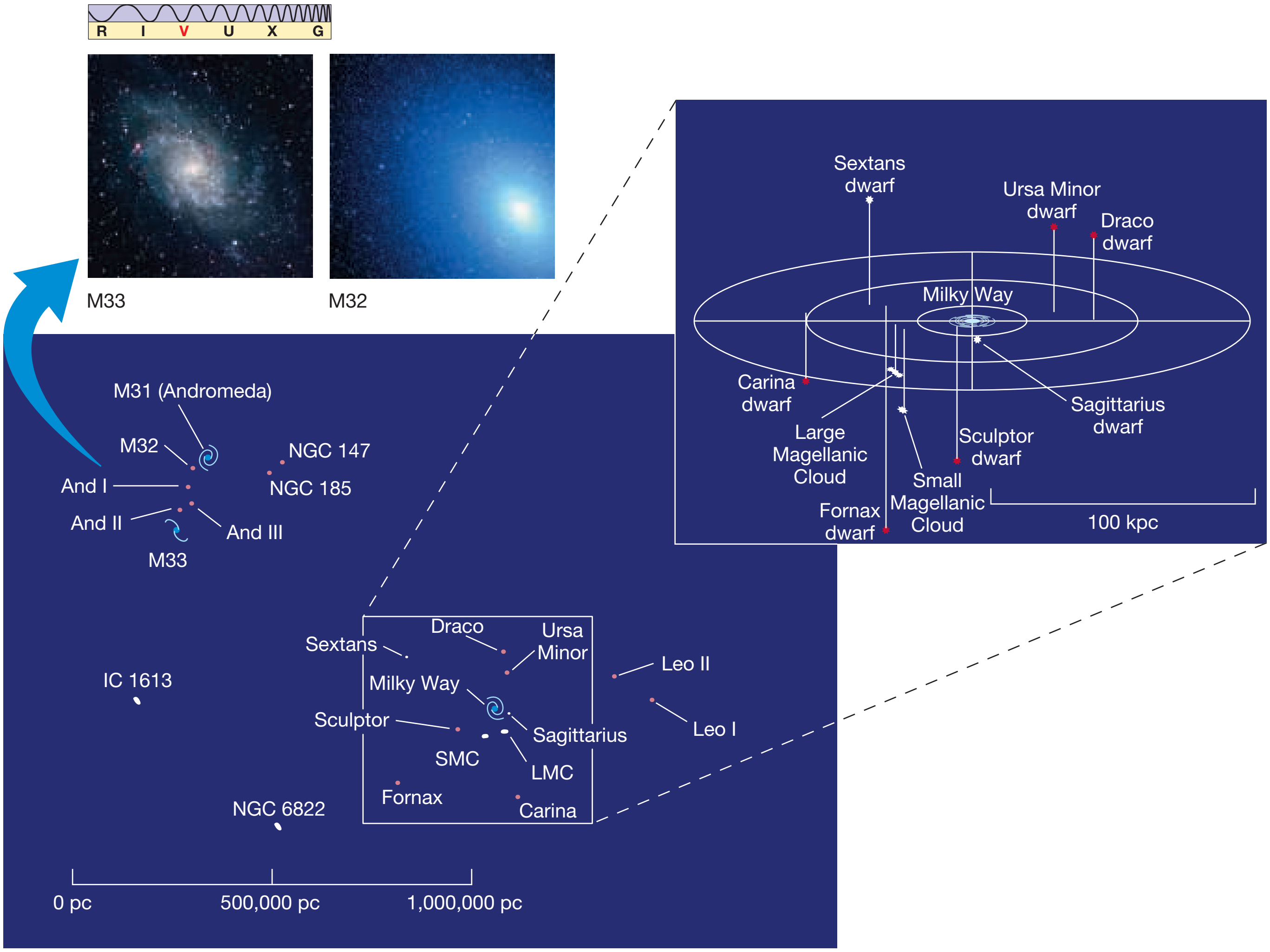
An important alternative to standard candles was discovered in the 1970s, when astronomers found a close correlation between the rotational speeds and the luminosities of spiral galaxies within a few tens of megaparsecs of the Milky Way Galaxy. Rotation speed is a measure of a spiral galaxy's total mass, so it is perhaps not surprising that this property should be related to luminosity. ∞ *(Sec. 14.5)* What *is* surprising, though, is how tight the correlation is. The **Tully–Fisher relation**, as it is now known (after its discoverers), allows us to obtain a remarkably accurate estimate of a spiral galaxy's luminosity simply by observing how fast it rotates (Figure 15.10). As usual, comparing the galaxy's (true) luminosity with its (observed) apparent brightness yields its distance.

The Tully–Fisher relation can be used to measure distances to spiral galaxies out to about 200 Mpc, beyond which the line broadening in Figure 15.10 becomes increasingly difficult to measure accurately. A somewhat similar connection, relating line broadening to a galaxy's *diameter,* exists for elliptical galaxies. Once the galaxy's diameter and angular diameter are known, its distance can be computed from elementary geometry. ∞ *(More Precisely 4-1)* These methods bypass many of the standard candles often used by astronomers and so provide independent means of determining distances to faraway objects.

As indicated in Figure 15.11, standard candles and the Tully–Fisher relation form the fifth and sixth rungs of our cosmic distance ladder, introduced in Chapter 1 and expanded in Chapters 10 and 14. ∞ *(Secs. 1.4, 10.6, 14.2)* In fact, they stand for perhaps a dozen or so related but separate techniques that astronomers have employed in their quest to map out the universe on large scales. Just as with the lower rungs, we calibrate the properties of these new techniques using distances measured by more local means. In this way, the distance-measurement process "bootstraps" itself to greater and greater distances. However, at the same time, the errors and uncertainties in each step accumulate, so the distances to the farthest objects are the least well known.



▲ **FIGURE 15.11 Extragalactic Distance Ladder INTERACTIVE** An inverted pyramid summarizes the distance techniques used to study different realms of the universe. The techniques shown in the bottom four layers—radar ranging, stellar parallax, spectroscopic parallax, and variable stars—take us as far as the nearest galaxies. To go farther, we must use other techniques—the Tully–Fisher relation and the use of standard candles, among other methods—based on distances determined by the four lowest techniques.



▲ **FIGURE 15.12 Local Group** The Local Group is made up of more than 50 galaxies within approximately 1 Mpc of our Milky Way Galaxy. Only a few are spirals; most are dwarf-elliptical or irregular galaxies, only some of which are shown here. Spirals are colored blue, ellipticals pink, and irregulars white, all of them depicted roughly to scale. The map inset (top right) shows the Milky Way in relation to some of its satellite galaxies. The photographic insets (top left) show two well-known neighbors of the Andromeda galaxy (M31): the spiral galaxy M33 and the dwarf elliptical galaxy M32 (also visible in Figure 14.2a, a larger-scale view of the Andromeda system). *(M. BenDaniel; NASA)*

Clusters of Galaxies

Figure 15.12 sketches the locations of all the known major astronomical objects within about 1 Mpc of the Milky Way. Our Galaxy appears with its dozen or so satellite galaxies—including the two Magellanic Clouds discussed earlier and a small companion (labeled "Sagittarius" in the figure) lying almost within our own Galactic plane. The Andromeda galaxy, lying 800 kpc from us, is also shown, surrounded by satellites of its own. Two of Andromeda's galactic neighbors are shown in the inset to the figure. M33 is a spiral, while M32 is a dwarf elliptical, easily seen in Figure 14.2(a) to the bottom right of Andromeda's central bulge.

All told, some 55 galaxies are known to populate our Galaxy's neighborhood. Three of them (the Milky Way, Andromeda, and M33) are spirals; the remainder are dwarf irregulars and dwarf ellipticals. Together, these galaxies form the **Local Group**—a new level of structure in the universe above the scale of our Galaxy. As

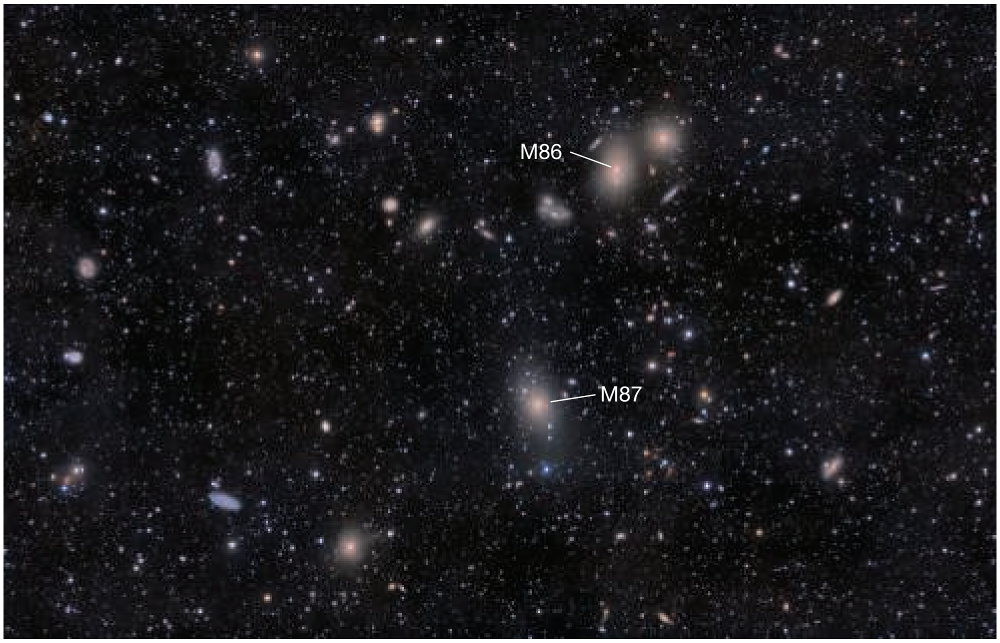


FIGURE 15.13 Virgo Cluster In the central region of the Virgo Cluster of galaxies, about 17 Mpc from Earth, many large spiral and elliptical galaxies can be seen. The inset shows several galaxies surrounding the giant elliptical M86. An even bigger elliptical galaxy, M87 noted at bottom, will be discussed later in this chapter. *(M. BenDaniel; AURA)*

indicated in Figure 15.12, the Local Group's diameter is a little over 1 Mpc. The Milky Way Galaxy and Andromeda are by far its largest members, and most of the smaller galaxies are gravitationally bound to one or other of them. The combined gravity of the galaxies in the Local Group binds them together, like stars in a star cluster, but on a scale a millionfold larger. More generally, a group of galaxies held together by their mutual gravitational attraction is called a **galaxy cluster.**

Moving beyond the Local Group, the next large concentration of galaxies we come to is the *Virgo Cluster* (Figure 15.13), named for the constellation in which it is found. It lies some 18 Mpc from the Milky Way. The Virgo Cluster does not contain a mere 45 galaxies, however. Rather, it houses more than 2500 galaxies, bound by gravity into a tightly knit group about 3 Mpc across.

Wherever we look in the universe we find galaxies, and most galaxies are members of galaxy clusters. Small clusters, such as the Local Group, contain only a few galaxies and are quite irregular in shape. Large, "rich" clusters such as Virgo contain thousands of individual galaxies distributed fairly smoothly in space. Abell S0740, shown in Figure 15.1, is another example of a rich cluster. It lies approximately 100 Mpc away. Figure 15.14 is a long-exposure photograph of a much more distant rich cluster, residing roughly 2 billion parsecs from Earth. A sizeable minority of galaxies (possibly as many as 40 percent) are not members of any cluster. They are apparently isolated systems, moving alone through intercluster space.

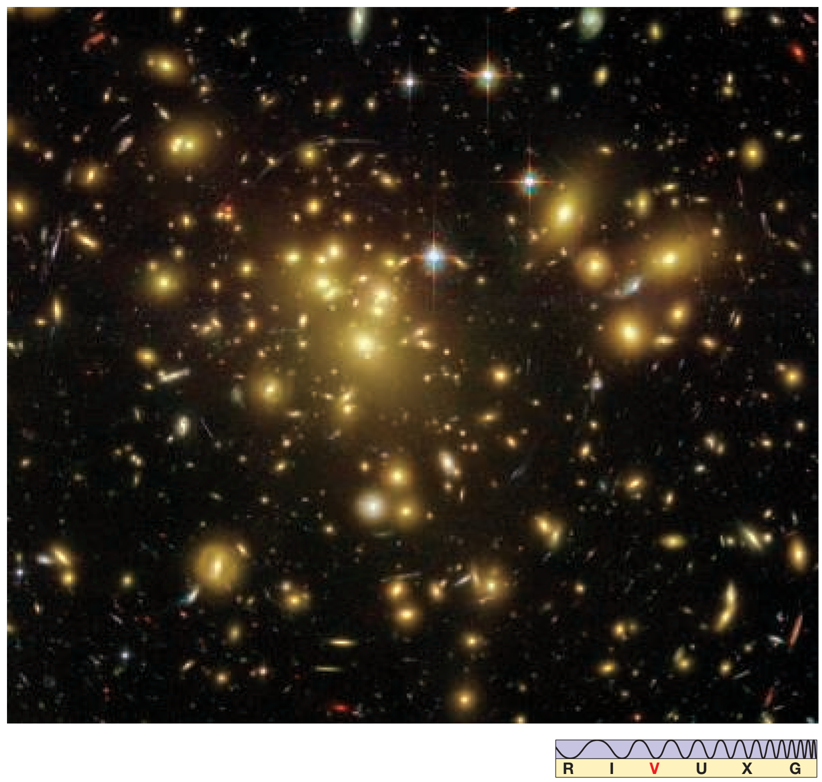


FIGURE 15.14 Distant Galaxy Cluster The galaxy cluster Abell 1689 contains huge numbers of galaxies and resides roughly 2 billion parsecs from Earth. Virtually every patch of light in this photograph is a separate galaxy. With the most powerful telescopes, astronomers can now discern, even at this great distance, spiral structure in some of the galaxies, as well as many galaxies colliding—some tearing matter from one another, others merging into single systems. *(NASA)*

CONCEPT CHECK

How does the use of Hubble's law differ from the other extragalactic distance-measurement techniques we have seen in this text?

15.3 Hubble's Law

Now that we have seen some basic properties of galaxies across the universe, let's turn our attention to the large-scale *motions* of galaxies and galaxy clusters. Within a galaxy cluster, individual galaxies move more or less randomly. You might expect that, on even larger scales, the clusters themselves would also have random, disordered motion—some clusters moving this way, some that, but this is not the case. On the largest scales, galaxies and galaxy clusters alike move in a very *ordered* way.

Universal Recession

In 1912 American astronomer Vesto M. Slipher, working under the direction of Percival Lowell, discovered that virtually every spiral galaxy he observed had a redshifted spectrum—they were *receding* from our Galaxy. ∞ *(Sec. 2.7)* In fact, with the exception of a few nearby systems, *every* known galaxy is part of a general motion away from us in all directions. Individual galaxies that are not part of galaxy clusters are steadily receding. Galaxy clusters, too, have an overall recessional motion, although their individual member galaxies move randomly with respect to one another. (Consider a jar full of fireflies that has been thrown into the air. The fireflies within the jar, like the galaxies within the cluster, have random motions due to their individual whims, but the jar as a whole, like the galaxy cluster, has some directed motion as well.)

▼ **FIGURE 15.15 Galaxy Spectra** Optical spectra (left) of several galaxies shown on the right. Both the extent of the redshift (denoted by the horizontal red arrows) and the distance from the Milky Way Galaxy to each galaxy (numbers in center column) increase from top to bottom. The vertical yellow arrows denote a pair of dark absorption lines in the observed spectra. The many white vertical lines at the top and bottom of each spectrum are laboratory references. *(Adapted from Palomar/Caltech)*

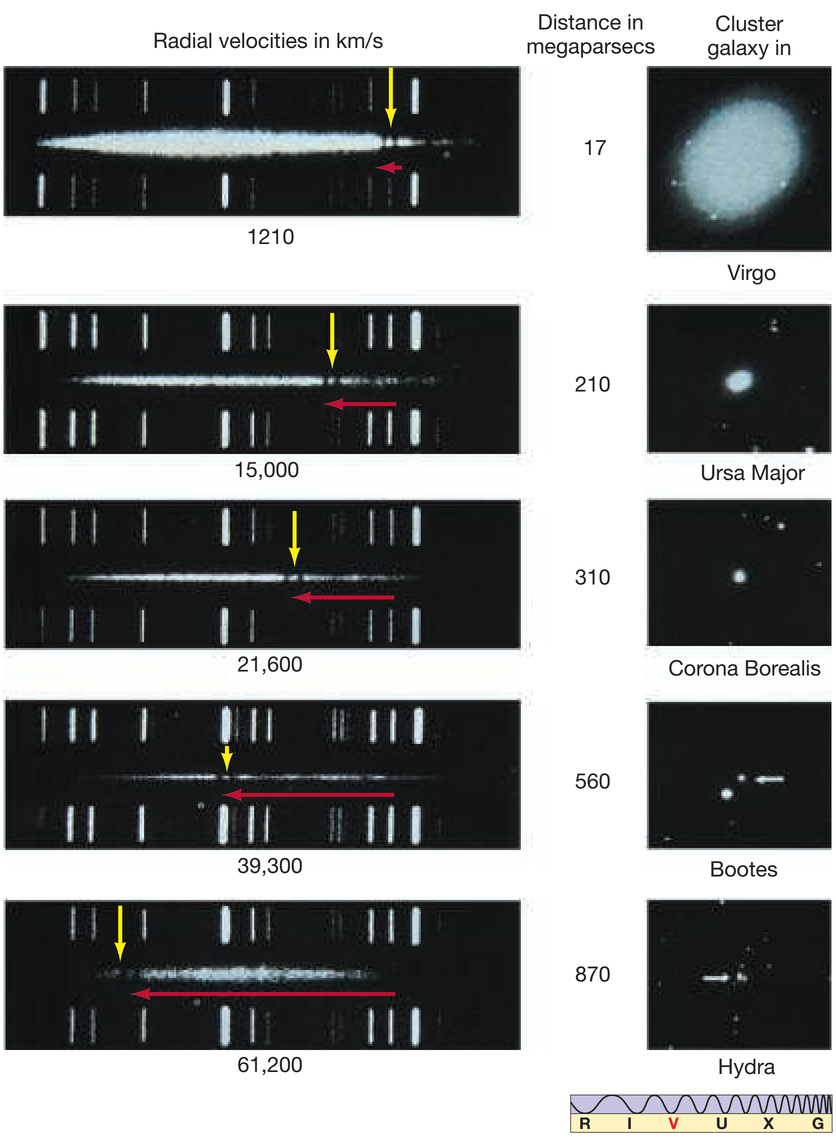


Figure 15.15 shows the optical spectra of several galaxies, arranged in order of increasing distance from the Milky Way Galaxy. These spectra are redshifted, indicating that the galaxies are receding, and the extent of the redshift increases from top to bottom in the figure. There is a connection between Doppler shift and distance: the greater the distance, the greater the redshift. This trend holds for nearly all galaxies in the universe. (Two galaxies within our Local Group, including Andromeda, and a few galaxies in the Virgo Cluster display blueshifts and so are moving toward us, but this results from their local motions within their parent clusters. Recall the fireflies in the jar.)

Figure 15.16(a) plots recessional velocity against distance for the galaxies shown in Figure 15.15. A similar plot for more galaxies within about 1 billion parsecs of Earth is shown in Figure 15.16(b). Plots like these were first made by Edwin Hubble in the 1920s and now bear his name—*Hubble diagrams*. The data points fall close to a straight line, indicating that the rate at which a galaxy recedes is *directly proportional* to its distance from us. This rule is called **Hubble's law**. We could construct such a diagram for any group of galaxies, provided we could determine their distances and velocities. The universal recession described by the Hubble diagram is called the *Hubble flow*.

The recessional motions of the galaxies prove that the cosmos is not steady and unchanging on the largest scales. The universe (actually, *space itself*—see Sec. 17.2) is expanding. But let's be clear on just *what* is expanding and what is not. Hubble's law does not mean that humans, Earth, the solar system, or even individual galaxies and galaxy clusters are physically increasing in size. These groups of atoms, rocks, planets, stars, and galaxies are held together by their own internal forces and are not