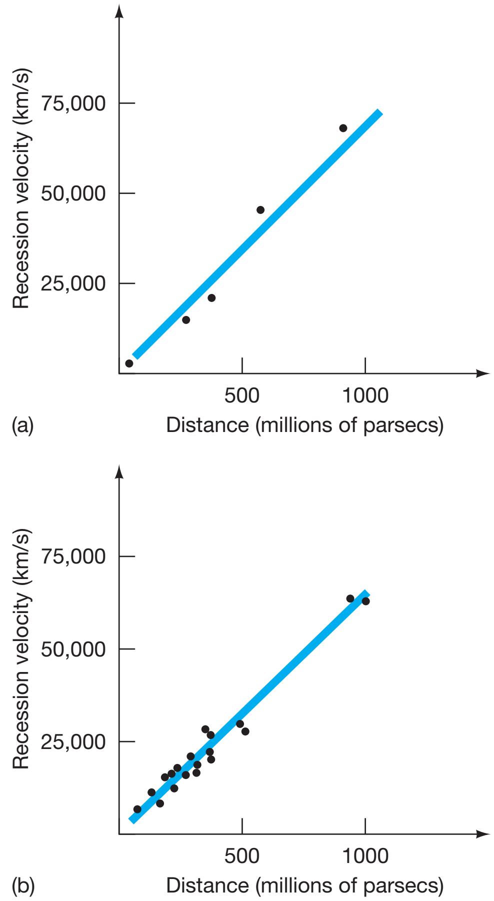
themselves getting bigger. Only the largest scales in the universe—the distances separating the galaxy clusters—are expanding.

To distinguish recessional redshift from redshifts caused by motion *within* an object—for example, galaxy orbits within a cluster or explosive events in a galactic nucleus—astronomers refer to the redshift resulting from the Hubble flow as the **cosmological redshift**. Objects that lie so far away that they exhibit a large cosmological redshift are said to be at *cosmological distances*—distances comparable to the scale of the universe itself.

Hubble's law has some fairly dramatic implications. If nearly all galaxies show recessional velocities according to Hubble's law, then doesn't that mean that they all started their journey from a single point? If we could run time backward, wouldn't all the galaxies fly back to this one point, perhaps the site of some explosion in the remote past? The answer is yes—but not in the way you might expect! In Chapter 17 we will explore the ramifications of the Hubble flow for the past and future evolution of our universe. For now, however, we set aside its cosmic implications and use Hubble's law simply as a convenient distance-measuring tool.



▲ **FIGURE 15.16 Hubble's Law INTERACTIVE** Plots of recessional velocity against distance (a) for the galaxies shown in Figure 15.15 and (b) for numerous other galaxies within about 1 billion pc of Earth.

Hubble's Constant

The constant of proportionality between recessional velocity and distance in Hubble's law is known as **Hubble's constant**, denoted by the symbol H_0. The data shown in Figure 15.16 then obey the equation:

$$\text{recessional velocity} = H_0 \times \text{distance}.$$

The value of Hubble's constant is the slope of the straight line—recessional velocity divided by distance—in Figure 15.16(b). Reading the numbers off the graph, this comes to roughly 70,000 km/s divided by 1000 Mpc, or 70 km/s/Mpc (kilometers per second per megaparsec, the most commonly used unit for H_0). Astronomers continually strive to refine the accuracy of the Hubble diagram and the resulting estimate of H_0 because Hubble's constant is one of the most fundamental quantities of nature—it specifies the rate of expansion of the entire cosmos.

Hubble's original value for H_0 was about 500 km/s/Mpc, far higher than the currently accepted value. This overestimate was due almost entirely to errors in the cosmic distance scale at the time, particularly the calibrations of Cepheid variables and standard candles. The measured value dropped rapidly as various observational errors were recognized and resolved and distance measurements became more reliable. Published estimates of H_0 entered the "modern" range (within, say, 20 percent of the current value) in roughly the mid-1960s.

As measurement techniques have continued to improve, the uncertainty in the result has steadily decreased to the point that now, early in the 21st century, all leading measurements of H_0, determined by a variety of different techniques—Tully–Fisher measurements, studies of Cepheid variables in the Virgo cluster, and observations of standard candles, such as Type I supernovae—are all remarkably consistent with one another. We will adopt a rounded-off value of $H_0 = 70$ km/s/Mpc (a choice roughly in the middle of all recent results and also in line with some precise cosmological measurements to be discussed in Chapter 17) as the best current estimate of Hubble's constant for the remainder of the text.

The Top of the Distance Ladder

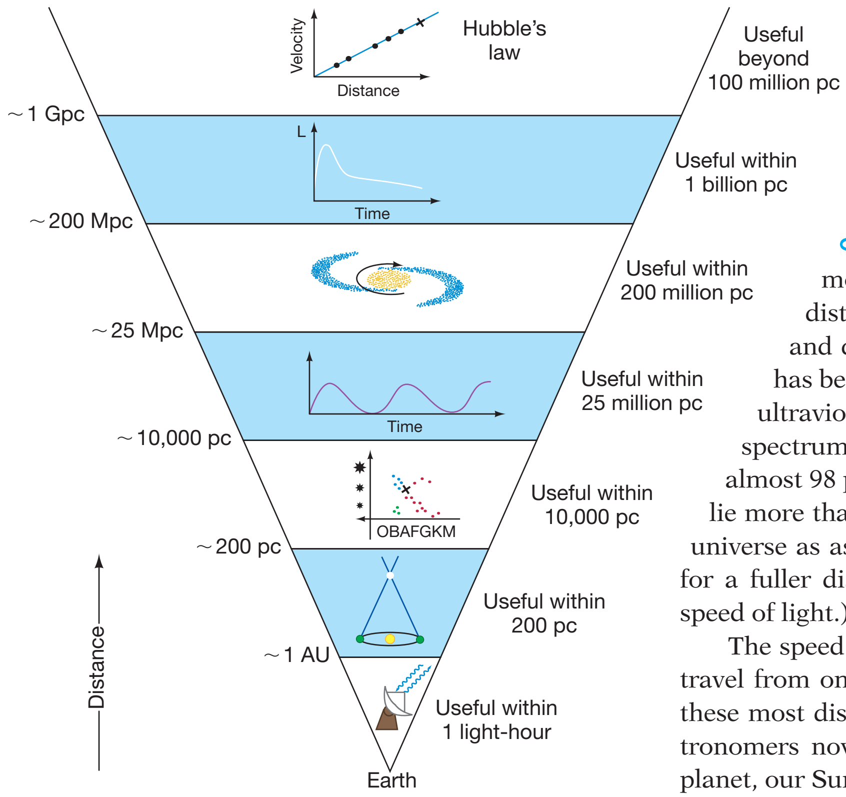
Using Hubble's law, we can derive the distance to a remote object simply by measuring the object's recessional velocity and dividing by Hubble's constant. Hubble's law thus tops our inverted pyramid of distance-measurement techniques (Figure 15.17). This seventh method simply assumes that Hubble's law holds. If this assumption is correct, then Hubble's law enables us to measure great

DATA POINTS

Hubble's Law

More than half of all students had difficulty describing and using Hubble's Law. Some points to remember:

- Hubble's Law is an observed relation between a galaxy's distance and the speed with which it moving away from us—on average, the more distant a galaxy, the greater its recession velocity.
- If we plot galaxy distances horizontally and velocities vertically, Hubble's law means that galaxies lie approximately on a straight line on the graph. The slope of that line is Hubble's constant, a direct measure of the expansion of the universe.
- Hubble's law allows us to measure the distance to a galaxy simply by measuring its recession velocity. Dividing the velocity (in km/s) by Hubble's constant (in km/s/Mpc) gives us the distance in megaparsecs.



▲ **FIGURE 15.17 Cosmic Distance Ladder INTERACTIVE** Hubble's law tops the hierarchy of distance-measurement techniques. It is used to find the distances of astronomical objects all the way out to the limits of the observable universe.

distances in the universe—so long as we can obtain an object's spectrum, we can determine how far away it is.

The precise astronomical definition of *redshift* is the fractional increase in the wavelength of a beam of radiation due to the source's motion away from us. For many nearby objects, recession velocities are small compared to the speed of light, and the redshifts are correspondingly low—just a few percent. ∞ *(Sec. 2.7)* However, more distant objects can have recessional motions that are substantial fractions of the speed of light. The most distant objects thus far observed in the universe—some young galaxies and quasars—have redshifts of around 8, meaning that their radiation has been stretched in wavelength not by a few percent, but *ninefold*. Their ultraviolet spectral lines are shifted all the way into the infrared part of the spectrum! Such huge redshifts correspond to recessional velocities of more almost 98 percent of the speed of light. Hubble's law implies that such objects lie more than 9000 Mpc away from us, as close to the limits of the observable universe as astronomers have yet been able to probe. (See *More Precisely 15-1*, for a fuller discussion of redshifts and recession velocities comparable to the speed of light.)

The speed of light is finite. It takes time for light or any kind of radiation to travel from one point in space to another. The radiation that we now see from these most distant objects originated long ago. Incredibly, the radiation that astronomers now detect was emitted roughly billion years ago, well before our planet, our Sun, and perhaps even our Galaxy came into being.

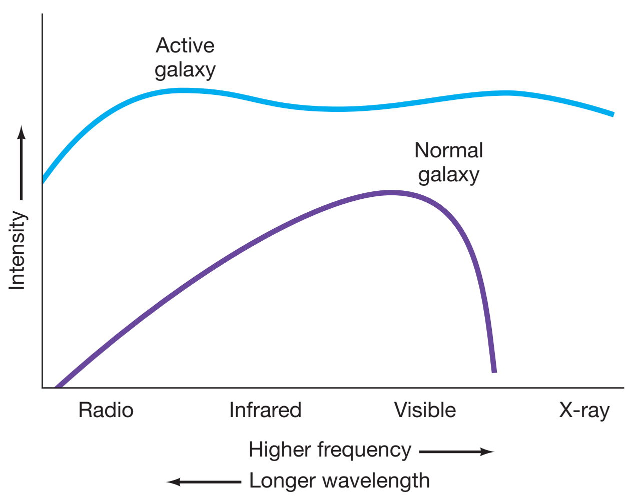
15.4 Active Galactic Nuclei

The galaxies described in Section 15.1—those falling into the various Hubble classes—are generally referred to as **normal galaxies.** As we have seen, their luminosities range from a million or so times that of the Sun for dwarf ellipticals and irregulars to more than a trillion solar luminosities for the largest giant ellipticals. For comparison, in round numbers, the luminosity of the Milky Way Galaxy is 2×10^{10} solar luminosities, or roughly 10^{37} W.

In these last two sections we focus our attention on "bright" galaxies, conventionally taken to mean galaxies with luminosities more than about 10^{10} times the solar value. By this measure, our Galaxy is bright, but not abnormally so.

Galactic Radiation

A substantial fraction of bright galaxies—perhaps as many as 40 percent—don't fit well into the "normal" category. Their *spectra* differ significantly from those of their normal cousins, and their *luminosities* can be extremely large. Known collectively as **active galaxies,** they are of great interest to astronomers. The brightest among them are the most energetic objects known in the universe, and all may represent an important, if intermittent, phase of galactic evolution (see Section 16.4). At optical wavelengths, active galaxies often *look* like normal galaxies—familiar components such as disks, bulges, stars, and dark dust lanes can be identified. At other wavelengths, however, their unusual properties are much more apparent.



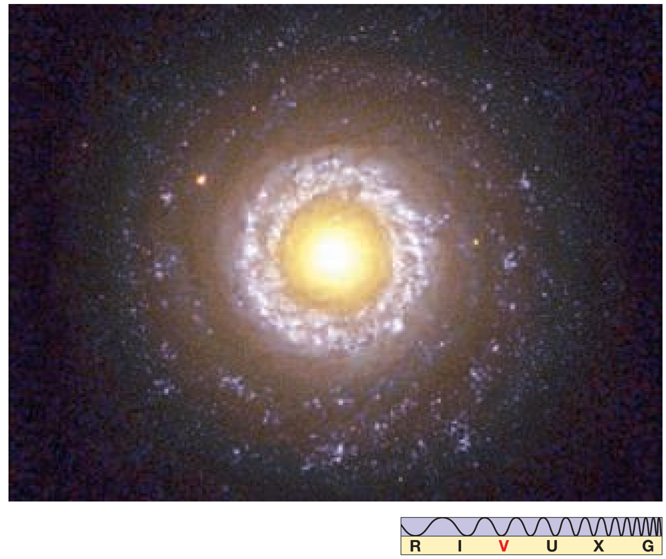
▲ **FIGURE 15.18 Galaxy Energy Spectra** The energy emitted by a normal galaxy differs significantly from that emitted by an active galaxy. This plot illustrates the general spread of radiation intensity for all galaxies of a particular type and does not represent any one individual galaxy.

As illustrated schematically in Figure 15.18, most of a normal galaxy's energy is emitted in or near the visible portion of the electromagnetic spectrum, much like the radiation from stars. Indeed, to a large extent, the light we see from a normal galaxy *is* just the accumulated light of its many component stars (once the effects of interstellar dust are taken into account), each described approximately by a blackbody curve. ∞ *(Sec. 2.4)* By contrast the radiation from active galaxies does *not* peak in the visible portion of the spectrum. Most active galaxies do emit substantial amounts of visible radiation, but far more of their energy is emitted at invisible wavelengths, both longer and shorter than those in the visible range. Put another way, the radiation from active galaxies is *inconsistent* with what we would expect if it were the combined radiation of billions of stars. Their radiation is said to be *nonstellar.*

Many luminous galaxies with nonstellar emission are known to be **starburst galaxies**—previously normal systems currently characterized by widespread episodes of star formation, most likely as a result of interactions with a neighbor. The irregular galaxy NGC 1569 shown in Figure 15.8(b) is a prime example. We will study these important systems and their role in galaxy evolution in Chapter 16. For purposes of this text, however, we will use the term "active galaxy" to mean a system whose abnormal activity is related to violent events occurring in or near the galactic nucleus. The nuclei of such systems are called **active galactic nuclei**.

Astronomers have identified and cataloged a bewildering array of systems falling into the "active" category. For example, Figure 15.19 shows an active galaxy exhibiting both nuclear activity and widespread star formation, with a blue-tinted ring of newborn stars surrounding an extended 1-kpc-wide core of intense emission. Rather than attempting to describe the entire "zoo" of active galaxies, we will confine ourselves to three basic types: the energetic *Seyfert galaxies* and *radio galaxies,* and the even more luminous *quasars*. Their properties will allow us to identify and discuss features common to active galaxies in general.

The association of galactic activity with the galactic nucleus is reminiscent of the discussion of the center of the Milky Way in Chapter 14. ∞ *(Sec. 14.7)* In our Galaxy, it seems that the activity in the nucleus is associated with the central *supermassive black hole,* whose presence is inferred from observations of stellar orbits in the innermost fraction of a parsec. As we will see, most astronomers think that basically the same thing occurs in the nuclei of active galaxies and that "normal" and "active" galaxies may differ principally in the degree to which the nonstellar nuclear component of the radiation outshines the light from the rest of the galaxy. This is a powerful unifying theme for understanding the evolution of galaxies, and we will return to it in Chapter 16. For the remainder of this chapter, we concentrate on describing the properties of active galaxies and the black holes that power them.



▲ **FIGURE 15.19 Active Galaxy** This image of the galaxy NGC 7742 resembles a fried egg, with a ring of blue star-forming regions surrounding a very bright yellow core that spans about 1 kpc. This active galaxy combines star formation with intense emission from its central nucleus and lies roughly 24 Mpc away. *(NASA)*

CONCEPT CHECK

The energy emission from an active galactic nucleus does not resemble a blackbody curve. Why is this important?

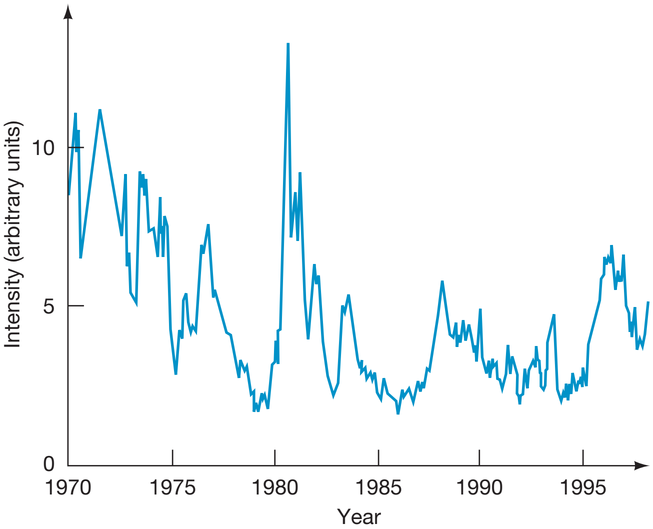
Seyfert Galaxies

In 1943 Carl Seyfert, an American optical astronomer studying spiral galaxies from Mount Wilson Observatory, discovered the type of active galaxy that now bears his name. **Seyfert galaxies** are a class of astronomical objects whose properties lie between normal galaxies and the most energetic active galaxies known.

Superficially, Seyferts resemble normal spiral galaxies (Figure 15.20). Indeed, the stars in a Seyfert's galactic disk and spiral arms produce about the same amount of visible radiation as the stars in a normal spiral galaxy. However, most of a Seyfert's energy is emitted from the galactic nucleus the center of the overexposed white patch in Figure 15.20. The nucleus of a Seyfert galaxy is some 10,000 times brighter than the center of our own Galaxy. In fact, the brightest Seyfert nuclei are 10 times more energetic than the *entire* Milky Way.

Some Seyferts produce radiation spanning a broad range in wavelengths, from the infrared all the way through ultraviolet and even X-rays. However, the majority (about 75 percent) emit most of their energy in the infrared. Scientists think that much of the high-energy radiation in these Seyferts is absorbed by dust in or near the nucleus, then reemitted as infrared radiation.

▲ **FIGURE 15.20 Seyfert Galaxy** NGC 1566, a beautiful Sb/c spiral, lies about 13 Mpc away in the southern constellation Dorado. Its bright, compact nucleus also identifies it as a Seyfert galaxy—in fact, one of the brightest known. This infrared/optical/ultraviolet composite image was obtained by *HST* in 2014. *(NASA/ESA)*



▲ **FIGURE 15.21 Seyfert Time Variability** This graph illustrates the irregular variations of the luminosity of Seyfert galaxy 3C 84 over three decades. These observations were made in the radio part of the electromagnetic spectrum; the optical and X-ray luminosities vary as well. *(NRAO)*

Seyfert spectral lines have many similarities to those observed toward the center of our own Galaxy. ∞ *(Sec. 14.7)* The lines are very broad, most likely indicating rapid (5000 km/s or more) internal motion within the nuclei. ∞ *(Sec. 2.8)* In addition, the energy emission often varies in time (Figure 15.21). A Seyfert's luminosity can double or halve within a fraction of a year. These rapid fluctuations in luminosity lead us to conclude that the source of energy emissions must be quite compact—simply put, an object cannot "flicker" in less time than radiation takes to cross it. ∞ *(Sec. 13.4)* The emitting region must therefore be less than 1 light-year across—an extraordinarily small region, considering the amount of energy emanating from it.

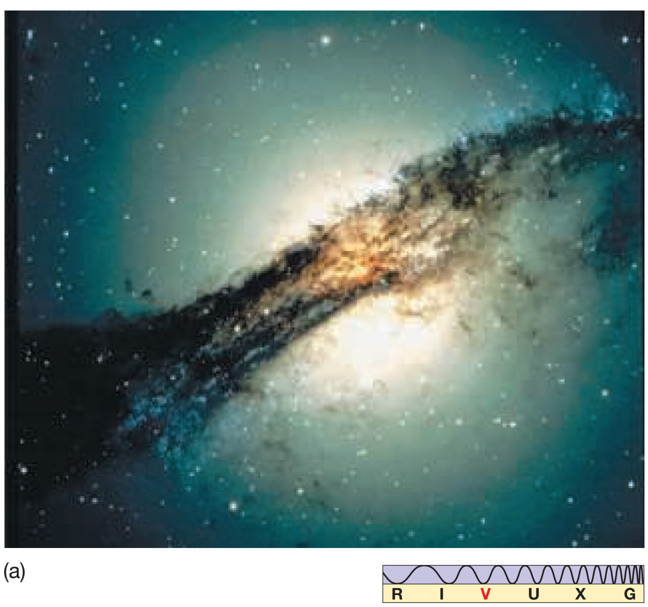
Taken together, the rapid time variability and large radio and infrared luminosities observed in Seyfert galaxies imply violent nonstellar activity in their nuclei. As just mentioned, this activity is probably similar in *nature* to processes occurring at the center of our own Galaxy, but its *magnitude* is thousands of times greater than the comparatively mild events within our own Galaxy's heart. ∞ *(Sec. 14.7)*

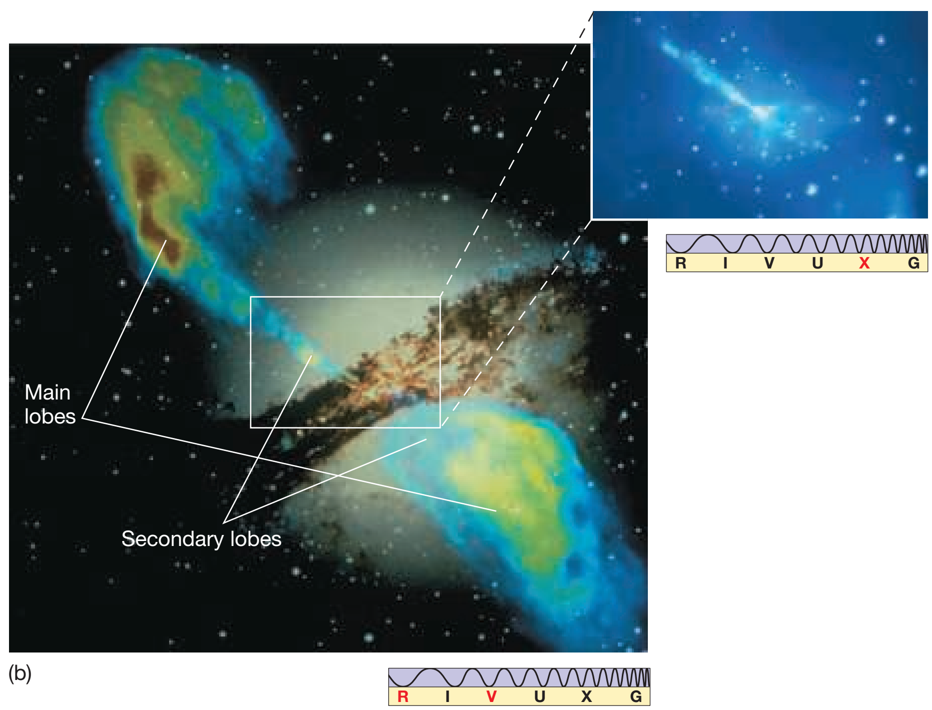
Radio Galaxies

As the name suggests, **radio galaxies** are active galaxies that emit large amounts of energy in the radio portion of the electromagnetic spectrum. They differ from Seyferts not only in the wavelengths at which they radiate, but also in both the appearance and the extent of their emitting regions.

Figure 15.22(a) shows the radio galaxy Centaurus A, which lies about 4 Mpc from Earth. Almost none of this galaxy's radio emission comes from a compact nucleus. Instead, the energy is released from two huge extended regions called **radio lobes**—roundish clouds of gas spanning about half a megaparsec, lying well beyond the visible galaxy.[1] Undetectable in visible light, the radio lobes of radio galaxies are truly enormous. From end to end, they typically span more than 10 times the size of the Milky Way Galaxy, comparable in scale to the entire Local Group.

[1]The term *visible galaxy* is commonly used to refer to those components of an active galaxy that emit visible "stellar" radiation, as opposed to the nonstellar and invisible "active" component of the galaxy's emission.





▲ **FIGURE 15.22 Centaurus A Radio Lobes** Radio galaxies, such as Centaurus A (a), often have giant radio-emitting lobes (b) extending a million light-years or more beyond the central galaxy. The lobes cannot be imaged in visible light and must be observed with radio telescopes; they are shown here in false color, with decreasing intensity from red to yellow to green to blue. The inset is a *Chandra* X-ray image of one of the lobes, showing that the jets in the inner parts of the lobes also emit higher-energy radiation. *(ESO; NRAO; SAO)*

▶ **FIGURE 15.23 Cygnus A** (a) A visible-light image of Cygnus A appears to show two galaxies in collision. (b) On a much larger scale, it displays radio-emitting lobes (mapped in blue) on both sides of the visible image. The galaxy in (a) is about the size of the small dot at the center of (b). The distance from one lobe to the other is approximately a million light-years. *(NOAO; NRAO)*

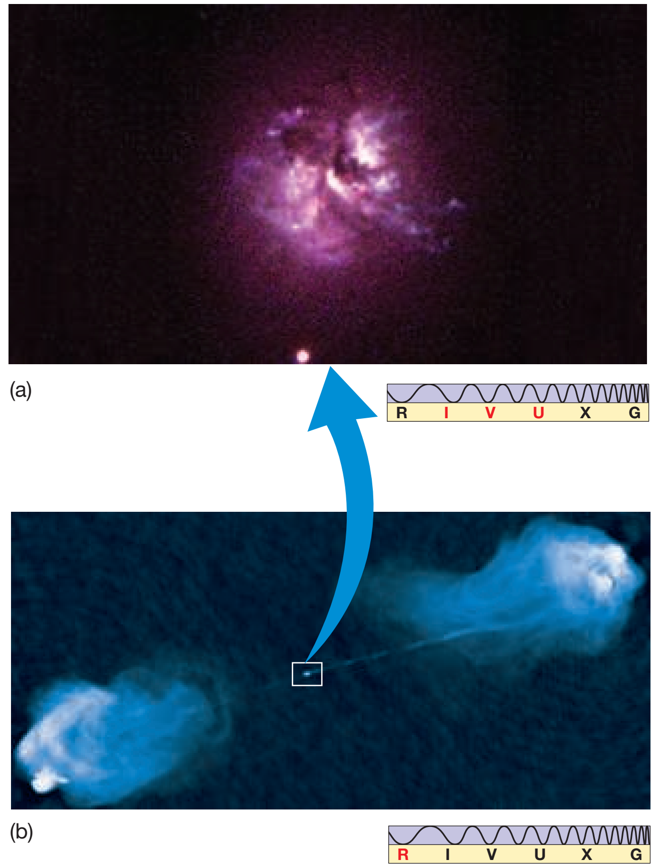


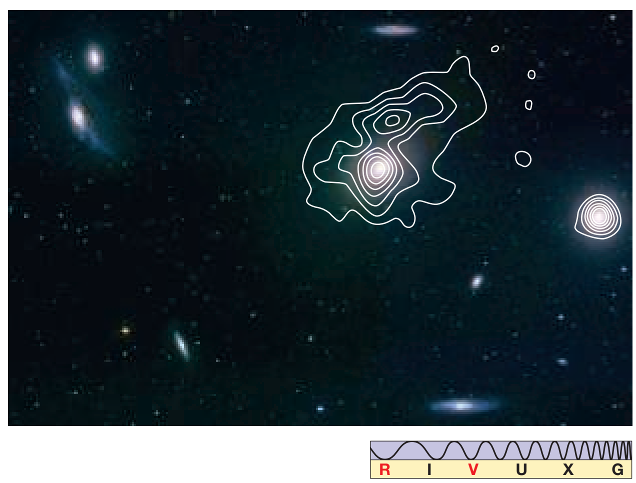
Figure 15.22(b) shows the relationship between the galaxy's visible, radio, and X-ray emission. In visible light, Centaurus A is apparently a large E2 galaxy some 500 kpc in diameter, bisected by an irregular band of dust. Centaurus A is a member of a small cluster of galaxies, and numerical simulations suggest that this peculiar galaxy is probably the result of a collision between an elliptical galaxy and a smaller spiral galaxy about 500 million years ago (see Chapter 16). The radio lobes are roughly symmetrically placed, jutting out from the center of the visible galaxy, roughly perpendicular to the dust lane, suggesting that they consist of material ejected in opposite directions from the galactic nucleus. This conclusion is strengthened by the presence of a pair of smaller secondary lobes closer to the visible galaxy and by the presence of a roughly 1-kpc-long jet of matter in the galactic center, all aligned with the main lobes (and marked in the figure).

If the material was ejected from the nucleus at close to the speed of light, then Centaurus A's outer lobes were created a few hundred million years ago, quite possibly around the time of the elliptical/spiral merger thought to be responsible for the galaxy's odd optical appearance. The secondary lobes were expelled more recently. Apparently, some violent process at the center of Centaurus A—most probably triggered by the collision—started up around that time and has been intermittently firing jets of matter out into intergalactic space ever since.

Centaurus A is a relatively low-luminosity source that happens to lie very close to us, astronomically speaking, making it particularly easy to study. Figure 15.23 shows a much more powerful emitter, called Cygnus A, lying roughly 250 Mpc from Earth. The high-resolution radio map in Figure 15.23(b) clearly shows two narrow, high-speed jets joining the radio lobes to the center of the visible galaxy (the dot at the center of the radio image). Notice also that, as with Centaurus A, Cygnus A is a member of a small group of galaxies, and the optical image (Figure 15.23a) appears to show a galaxy collision in progress.

The radio lobes of the brightest radio galaxies (such as Cygnus A) emit roughly 10 times more energy than the Milky Way Galaxy at all wavelengths, coincidentally about the same as the most luminous Seyfert nuclei. However, despite their names, radio galaxies actually radiate far more energy at shorter wavelengths. Their total energy output can be 100 times or more greater than their radio emission. Most of this energy comes from the nucleus of the visible galaxy. Having total luminosities up to 1000 times that of the Milky Way Galaxy, bright radio galaxies are among the most energetic objects known in the universe. Their radio emission is important to astronomers because it lets them study in detail the connection between the small-scale nucleus and the large-scale radio lobes.

Not all radio galaxies have obvious radio lobes. Figure 15.24 shows a *core-dominated* radio galaxy, most of whose energy is emitted from a small central nucleus (which radio astronomers refer to as the *core*) less than 1 pc across. Weaker radio emission comes from an extended region surrounding the nucleus. Probably all radio galaxies have jets and lobes, but what we observe depends on our perspective. As illustrated in Figure 15.25, when we view the radio galaxy from the side we see the jets and lobes. However, if a weak jet fails to escape from the parent galaxy, or if we view the jet almost head-on—in other words, looking *through* the lobe—then we see a core-dominated system.



▲ **FIGURE 15.24 Core-Dominated Radio Galaxy** As shown by this radio contour map of the galaxy M86, the radio emission comes from a bright central nucleus, which is surrounded by an extended region of less intense emission. The radio map is superimposed on an optical image of the galaxy and some of its neighbors, a wider-field version of which was shown previously in Figure 15.13. *(Harvard-Smithsonian Center for Astrophysics)*

15.1 MORE PRECISELY

Relativistic Redshifts and Look-Back Time

When discussing very distant objects, astronomers usually talk about their redshifts rather than their distances. Indeed, it is very common for researchers to speak of an event occurring "at" a certain redshift—meaning that the light received today from that event is redshifted by the specified amount. Of course, because of Hubble's law, redshift and distance are equivalent to one another. However, redshift is the preferred quantity because it is a directly observable property of an object, whereas distance is derived from redshift using Hubble's constant, whose value is not accurately known.

The redshift of a beam of light is, by definition, the *fractional* increase in its wavelength resulting from the recessional motion of the source. *(Sec. 2.7)* A redshift of 1 corresponds to a *doubling* of the wavelength. Using the formula for the Doppler shift given previously, the redshift of radiation received from a source moving away from us with speed v is

$$\text{redshift} = \frac{\text{observed wavelength} - \text{true wavelength}}{\text{true wavelengh}} = \frac{\text{recessional velocity, } v}{\text{speed of light, } c}.$$

Let's illustrate this with two examples, rounding the speed of light, c, to 300,000 km/s. A galaxy at a distance of 100 Mpc has a recessional speed (by Hubble's law) of 70 km/s/Mpc × 100 Mpc = 7000 km/s. Its redshift therefore is 7000 km/s ÷ 300,000 km/s = 0.023. Conversely, an object that has a redshift of 0.05 has a recessional velocity of and hence a distance of 0.05 × 300,000 km/s = 15,000 km/s and hence a distance of 15,000 km/s ÷ 70 km/s/Mpc = 210 Mpc.

Unfortunately, while the foregoing equation is correct for low speeds, it does not take into account the effects of relativity. As we saw in Chapter 13, the rules of everyday physics have to be modified when speeds begin to approach the speed of light, and the formula for the Doppler shift is no exception. *(More Precisely 13-1)* Our formula is valid for speeds much less than the speed of light, but when $v = c$, the redshift is not 1, as the equation suggests, but is in fact *infinite*. Radiation received from an object moving away from us at nearly the speed of light is redshifted to almost infinite wavelength.

Thus, do not be alarmed to find that many galaxies and quasars have redshifts greater than 1. This does not mean that they are receding faster than light! It simply means that their recessional speeds are relativistic—comparable to the speed of light—and the preceding simple formula is not applicable. Table 15.2 presents a conversion chart relating redshift, recession speed, and present distance. The column headed "v/c" gives recession velocities based on the Doppler effect, taking relativity properly into account (but see Section 17.2 for a more correct interpretation of the redshift). All values are based on reasonable assumptions and are usable even for $v \approx c$. We take Hubble's constant to be 70 km/s/Mpc and assume a flat universe (see Section 17.3 for details) in which matter (mostly dark) contributes just under one-third of the total density. The conversions in the table are used consistently throughout this text.

Because the universe is expanding, the "distance" to a galaxy is not very well defined—do we mean the distance when the galaxy emitted the light we see today or the present distance (as listed in the table), even though we do not see the galaxy as it is today, or is some other measure more appropriate? Largely because of this ambiguity, astronomers prefer to work in terms of a quantity known as the *look-back time* (last column of Table 15.2), which is simply how long ago an object emitted the radiation we see today. While astronomers talk frequently about redshifts and sometimes about look-back times, they hardly ever talk of distances to high-redshift objects.

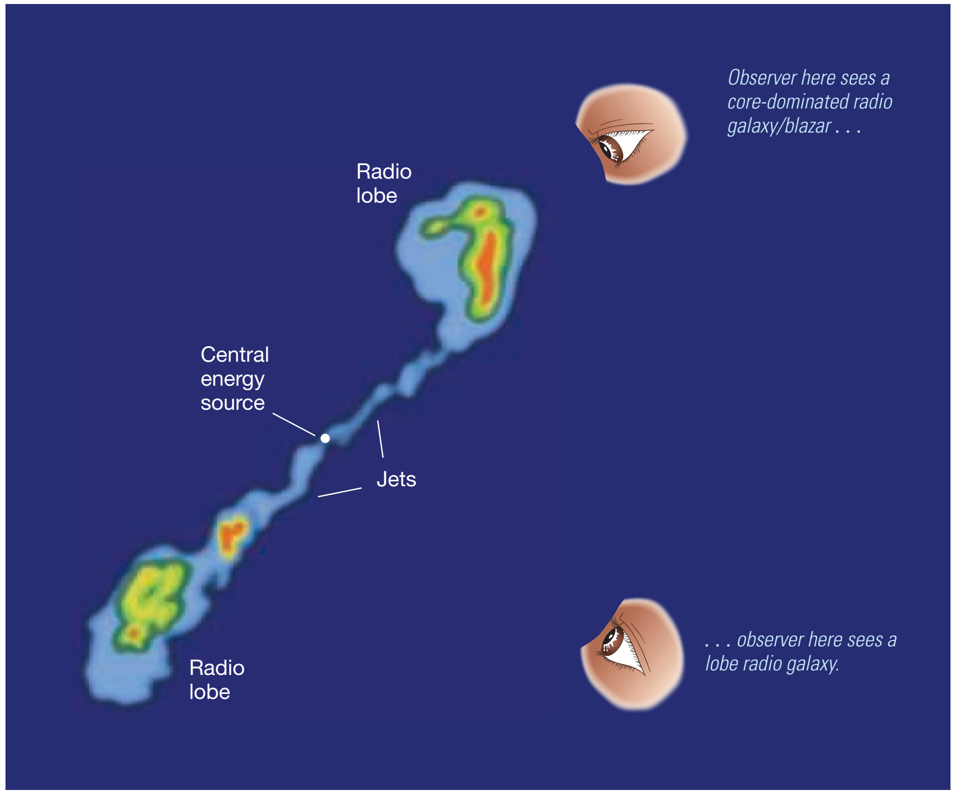
For nearby sources, the look-back time is numerically equal to the distance in light-years—the light we receive tonight from a galaxy at a distance of 100 million light-years was emitted 100 million years ago. However, for more distant objects, the look-back time and the present distance in light-years differ because of the expansion of the universe, and the divergence increases dramatically with increasing redshift (see Section 17.2). For example, a galaxy now located 15 billion light-years from Earth was much closer to us when it emitted the light we now see. Consequently, its light has taken considerably less than 15 billion years—in fact, a little less than 10 billion years—to reach us.

TABLE 15.2 Redshift, Distance, and Look-Back Time

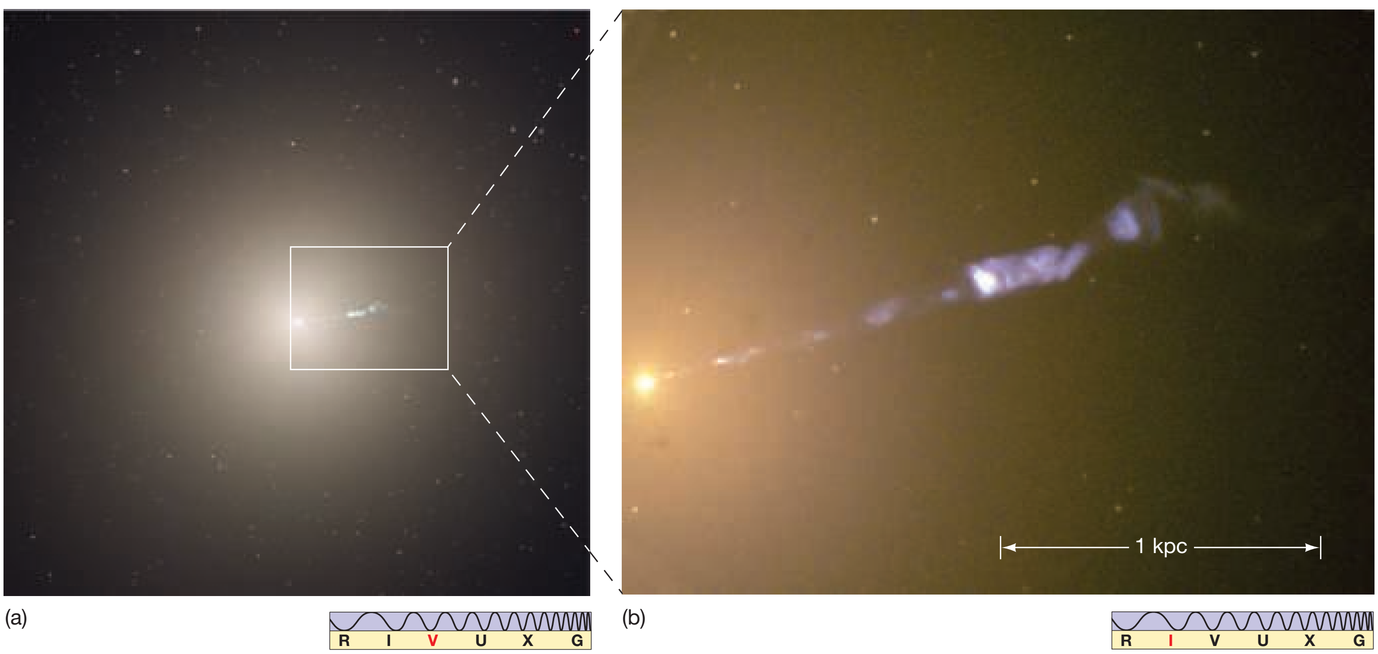
		Present Distance		Look-Back Time
Redshift	v/c	(Mpc)	(10^6 light-years)	(millions of years)
0.000	0.000	0	0	0
0.010	0.010	42	137	137
0.025	0.025	105	343	338
0.050	0.049	209	682	665
0.100	0.095	413	1,350	1,290
0.250	0.220	999	3,260	2,920
0.500	0.385	1,880	6,140	5,020
1.000	0.600	3,320	10,800	7,730
2.000	0.800	5,250	17,100	10,300
3.000	0.882	6,460	21,100	11,500
4.000	0.923	7,310	23,800	12,100
5.000	0.946	7,940	25,900	12,500
6.000	0.960	8,420	27,500	12,700
8.000	0.976	9,150	29,800	13,000
10.000	0.984	9,660	31,500	13,200
20.000	0.995	11,000	35,900	13,500
100.000	1.000	12,900	42,200	13,700
∞	1.000	14,600	47,500	13,700

Our precise location with respect to the jet can also radically affect the *type* of radiation we see. The theory of relativity tells us that radiation emitted by particles moving close to the speed of light is strongly concentrated, or beamed, in the direction of motion. ∞ *(More Precisely 13-1)* As a result, if the observer in Figure 15.25 happens to be directly in line with the beam, the radiation received will be both very intense and Doppler shifted toward short wavelengths. ∞ *(Sec. 2.7)* The resulting object is called a **blazar.** Much of the luminosity of the several hundred known blazars is received in the form of X-rays or gamma rays.

Jets are common in active galaxies of all types. Figure 15.26 presents several images of the giant elliptical galaxy M87, a prominent member of the Virgo Cluster (see the chapter-opening image on p. 418 and Figure 15.13). Detailed study of the central regions of this fairly normal looking E0 galaxy (Figure 15.26a) reveal that its core contains a long (2 kpc) thin jet of matter ejected from the galactic center at nearly the speed of light. Computer enhancement shows that it is made up of a series of distinct "blobs" more or less evenly spaced along its length, suggesting that the material was ejected during bursts of activity. The jet has also been imaged in the radio, infrared (Figure 15.26b), and X-ray regions of the spectrum.

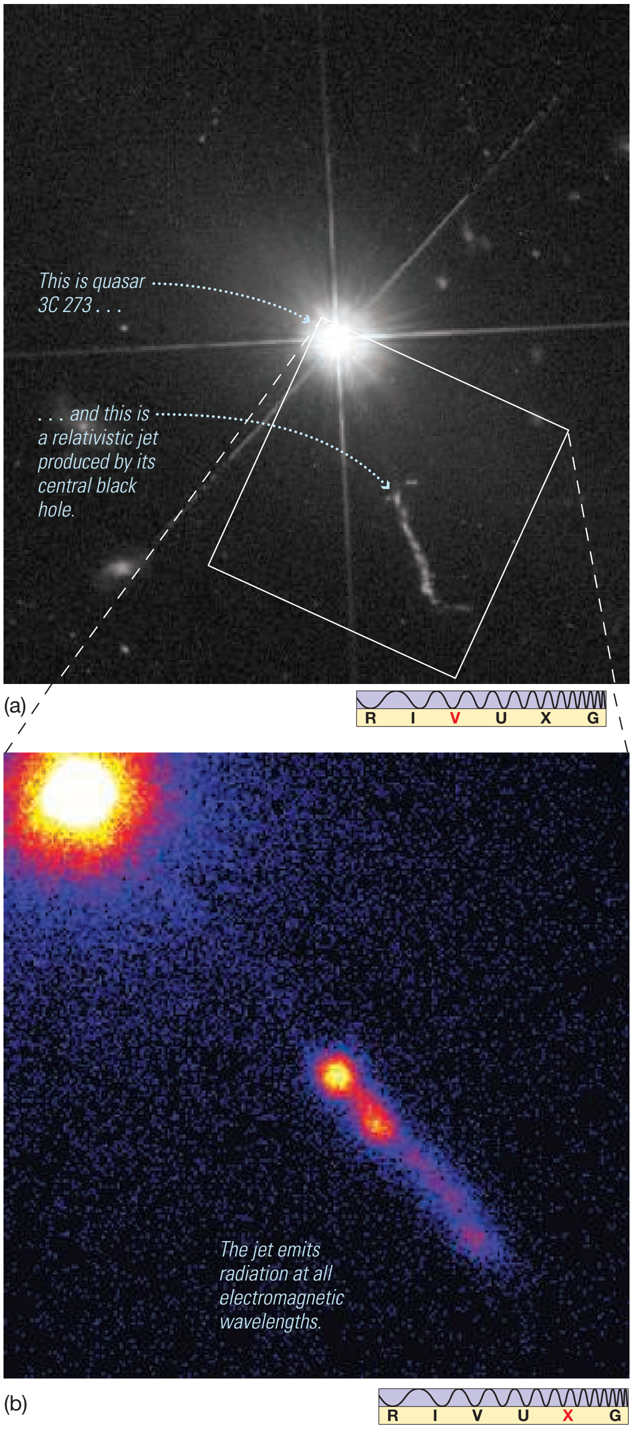


▲ **FIGURE 15.25 Radio Galaxy** A central energy source produces high-speed jets of matter that interact with intergalactic gas to form radio lobes. The system may appear to us as either radio lobes or a core-dominated radio galaxy, depending on our location with respect to the jets and lobes.



▲ **FIGURE 15.26 M87 Jet** INTERACTIVE (a) This *Hubble* image of the innermost 5 kpc of the giant elliptical M87 shows an intriguing jet of matter emerging from the galactic nucleus. (b) An infrared image of M87's jet, showing more detail. *(NASA/ESA)*

▼ **FIGURE 15.27 Quasar 3C 273** (a) The bright quasar 3C 273 displays a luminous jet of matter, but the main body of the quasar is starlike in appearance. The spikes are a camera artifact. (b) The jet extends for about 30 kpc and emits radiation across the electromagnetic spectrum, here in X-rays, as seen by *Chandra*. *(NASA/ESA)*



Quasars

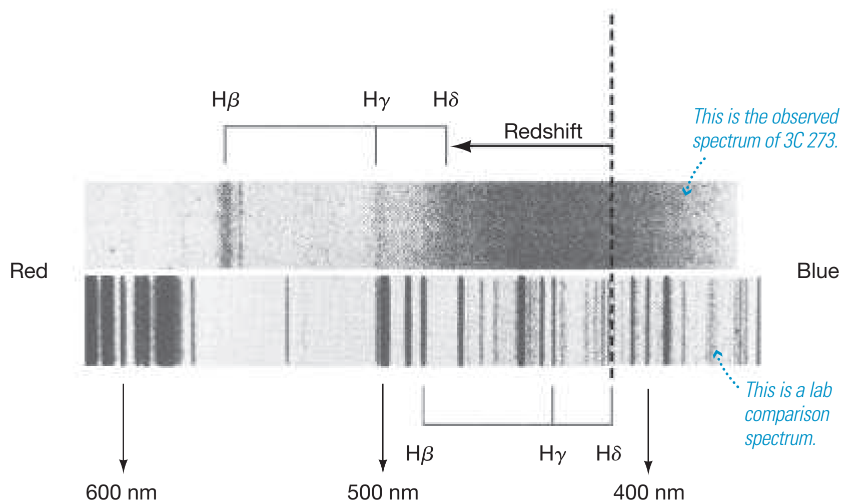
In the early days of radio astronomy, many radio sources were detected for which no corresponding visible object was known. By 1960 several hundred such sources were listed in the *Third Cambridge Catalog*, and astronomers were scanning the skies in search of visible counterparts to these radio sources. Their job was made difficult both by the low resolution of the radio observations (which meant that the observers did not know exactly where to look) and by the faintness of these objects at visible wavelengths.

In 1960 astronomers detected what appeared to be a faint blue star at the location of the radio source 3C 48 (the 48th object on the third *Cambridge* list) and obtained its spectrum. Containing many unknown broad emission lines, the unusual spectrum defied interpretation. 3C 48 remained a unique curiosity until 1962, when another similar-looking, and similarly mysterious, faint blue object with "odd" spectral lines was discovered and identified with the radio source 3C 273 (Figure 15.27).

The following year saw a breakthrough when astronomers realized that the strongest unknown lines in 3C 273's spectrum were simply familiar spectral lines of hydrogen redshifted by a very unfamiliar amount—about 16 percent, corresponding to a recession velocity of 48,000 km/s. Figure 15.28 shows the spectrum of 3C 273, with prominent emission lines and their redshifts marked. Once the nature of the strange spectral lines was known, astronomers quickly found a similar explanation for the spectrum of 3C 48. Its 37 percent redshift implied that it is receding from Earth at almost one-third the speed of light.

These huge speeds mean that neither of these two objects can possibly be members of our Galaxy. In fact, their large redshifts mean that they are very far away indeed. Applying Hubble's law (with our adopted value of the Hubble constant H_0 = 70 km/s/Mpc), we obtain distances of 650 Mpc for 3C 273 and 1400 Mpc for 3C 48. (See *More Precisely 15-1* and Chapter 17 for an account of how these distances are determined and an explanation of what these large redshifts really mean.)

However, this explanation of the unusual spectra created a greater mystery. A simple calculation using the inverse-square law reveals that despite their unimpressive optical appearance these faint "stars" are in fact the brightest known objects in the universe! ∞ ***(Sec. 10.2)*** 3C 273, for example, has a luminosity of about 10^{40} W, comparable to 20 trillion Suns or 1000 Milky Way Galaxies. More generally, quasars range in luminosity from around 10^{38} W—about the same as the brightest Seyferts—up to nearly 10^{42} W. A value of 10^{40} W (comparable to the luminosity of a bright radio galaxy) is fairly typical.



▶ **FIGURE 15.28 Quasar Spectrum** Optical spectrum of the distant quasar 3C 273. (This is a negative, as the lines are actually in emission.) Notice the redshift of the three hydrogen spectral lines marked as Hβ, Hγ, and Hδ. ∞ ***(Sec. 2.6)*** The widths of these lines imply rapid internal motion within the quasar. *(Adapted from Palomar/Caltech)*

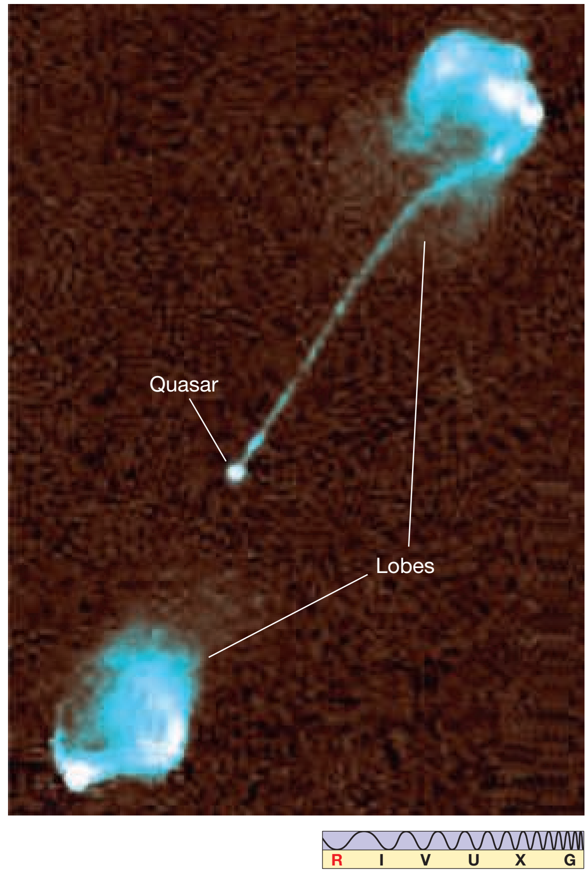
Clearly not stars (with such enormous luminosities), these objects became known as *quasi-stellar radio sources* (quasi-stellar means "starlike"), or **quasars.** Because we now know that not all such highly redshifted, starlike objects are strong radio sources, the term **quasi-stellar object** (or QSO) is more common today. However, the name quasar persists, and we will continue to use it here. More than 200,000 quasars are now known, and the numbers are increasing rapidly as large-scale surveys probe deeper and deeper into space. The distance to the *closest* quasar is 240 Mpc; the farthest lies some 9000 Mpc away. Most quasars lie well over 1000 Mpc from Earth. Since light travels at a finite speed, these faraway objects represent the universe as it was in the distant past. Most quasars date back to much earlier periods of galaxy formation and evolution, rather than more recent times. The prevalence of these energetic objects at great distances tells us that the universe was once a much more violent place than it is today.

Quasars share many properties with Seyferts and radio galaxies. Their radiation is nonstellar and may vary irregularly in brightness over periods of months, weeks, days, or (in some cases) even hours. Some show evidence of jets and extended emission features. Note the luminous jet in 3C 273 (Figure 15.27), reminiscent of the jet in M87 and extending nearly 30 kpc from the center of the quasar. Figure 15.29 shows a quasar with radio lobes similar to those in Cygnus A (Figure 15.23b). Quasars have been observed in all parts of the electromagnetic spectrum, but many emit most of their energy in the infrared. About 10–15 percent of quasars (called "radio-loud" quasars) also emit substantial amounts of energy at radio wavelengths, presumably as a result of unresolved jets.

Astronomers once distinguished between active galaxies and quasars on the basis of their appearance, spectra, and distance from us, but today most astronomers think that quasars are in fact just the intensely bright nuclei of distant active galaxies lying too far away for the galaxies themselves to be seen. (Figure 16.18 presents *Hubble Space Telescope* observations of two relatively nearby quasars in which the surrounding galaxies are clearly visible.)

PROCESS OF SCIENCE CHECK

How did the determination of quasar distances change astronomers' understanding of these objects?



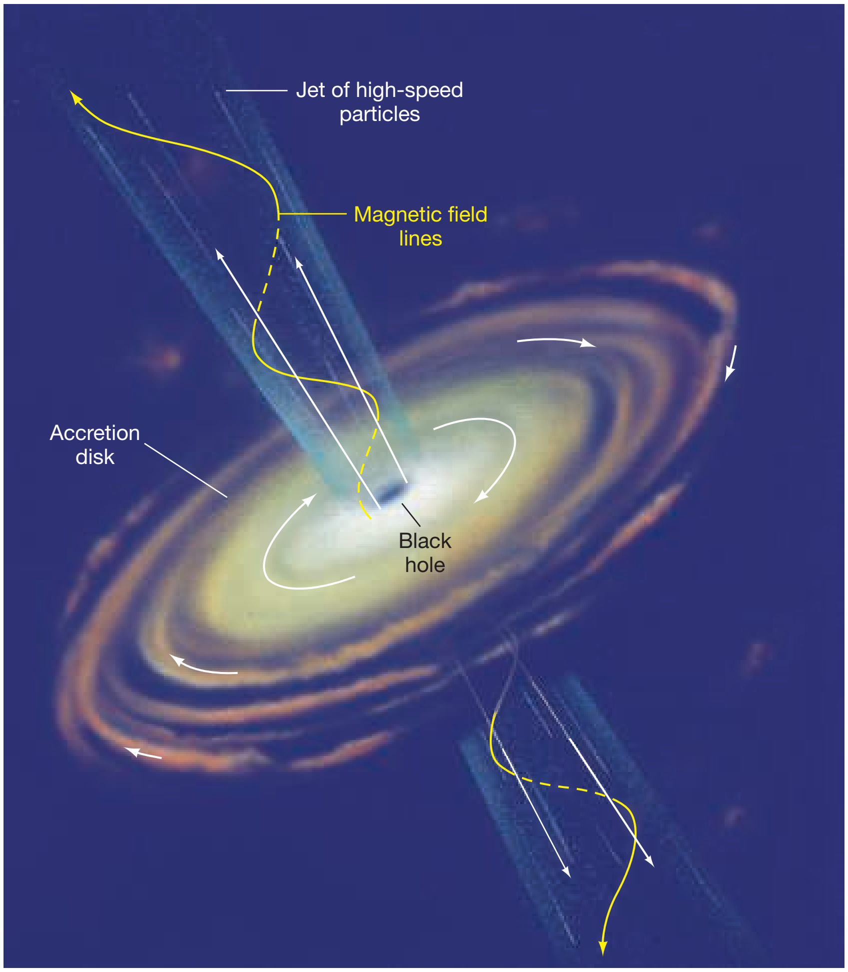
▲ **FIGURE 15.29 Quasar Jets** This radio image of the quasar 3C 175, which is some 3000 Mpc away, shows radio jets feeding faint radio lobes. The lobes span approximately a million light-years—comparable in size to the radio galaxies discussed earlier. *(NRAO)*

15.5 The Central Engine of an Active Galaxy

The present consensus among astronomers is that, despite their differences in appearance and luminosity, Seyferts, radio galaxies, and quasars share a common energy-generation mechanism. As a class, active galactic nuclei have some or all of the following properties:

1. They have *high luminosities,* generally greater than the 10^{37} W characteristic of a bright normal galaxy.
2. Their energy emission is mostly *nonstellar*—it cannot be explained as the combined radiation of even trillions of stars.
3. Their energy output can be highly *variable,* implying that it is emitted from a small central nucleus much less than a parsec across.
4. They often exhibit *jets* and other signs of explosive activity.
5. Their optical spectra may show broad emission lines, indicating *rapid internal motion* within the energy-producing region.
6. Often the activity appears to be associated with *interactions* between galaxies.

The principal questions then are: How can such vast quantities of energy arise from these relatively small regions of space? Why is the radiation nonstellar? And what is the origin of the jets and extended radio-emitting lobes? We first consider how the energy is *produced,* then turn to the question of how it is actually *emitted* into intergalactic space.



▲ **FIGURE 15.30 Active Galactic Nucleus** The leading theory for the energy source in active galactic nuclei holds that these objects are powered by material accreting onto a supermassive black hole. As matter spirals toward the hole, it heats up, producing large amounts of energy. High-speed jets of gas may be ejected perpendicular to the accretion disk, forming the jets and lobes seen in many active objects. Magnetic fields generated in the disk by charged matter in motion are carried by the jets out to the radio lobes, where they play a crucial role in producing the observed radiation.

ANIMATION/VIDEO MA
Cosmic Jets

Energy Production

As illustrated in Figure 15.30, the leading model for the central engines of active galaxies is a scaled-up version of the process powering X-ray binaries in our Galaxy and the activity in the Galactic center—accretion of gas onto a supermassive black hole, releasing huge amounts of energy as the matter sinks onto the central object. ∞ *(Secs. 13.3, 13.8, 14.7)* In order to power the brightest active galaxies, theory suggests that the black holes involved must be *billions* of times more massive than the Sun.

As with this model's smaller-scale counterparts, infalling gas forms an accretion disk and spirals down toward the black hole. It is heated to high temperatures by friction within the disk and emits large amounts of radiation as a result. In this case, however, the origin of the accreted gas is not a binary companion, as in stellar X-ray sources, but rather entire stars and clouds of interstellar gas, most likely diverted into the galactic center by an encounter with another galaxy, that come too close to the hole and are torn apart by its strong gravity.

Accretion is extremely efficient at converting infalling mass (in the form of gas) into energy (in the form of electromagnetic radiation). As much as 10 or 20 percent of the total mass–energy of the infalling matter can be radiated away before it crosses the hole's event horizon and is lost forever. ∞ *(Sec. 13.5)* Since the total mass–energy of a star like the Sun—the mass times the speed of light squared—is about 2×10^{47} J, it follows that the 10^{38} W luminosity of a bright active galaxy can be produced by the consumption of "only" 1 solar mass of gas per decade by a billion-solar-mass black hole. More or less luminous active galaxies would require correspondingly more or less fuel. To power a 10^{40}-W quasar, which is 100 times brighter, the black hole consumes 100 times more fuel, or 10 stars per year. The central black hole of a 10^{36}-W Seyfert galaxy would devour only one Sun's worth of material every thousand years.

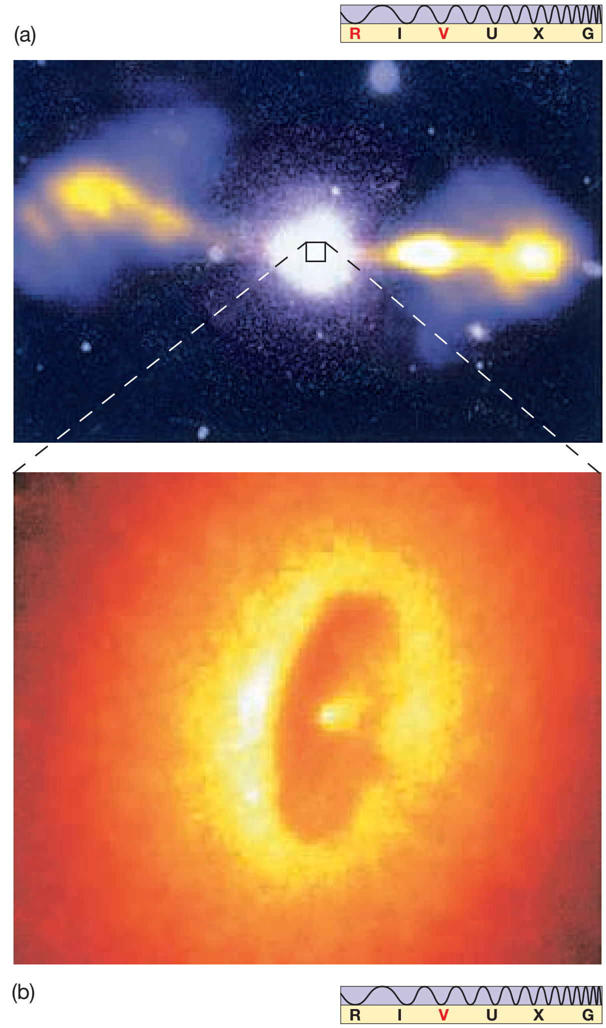
Even a billion-solar-mass black hole has a radius of only 3×10^9 km, or 10^{-4} pc—about 20 AU—so the part of the accretion disk responsible for most of the emission is much less than 1 pc across. ∞ *(Sec. 13.5)* Instabilities in the disk cause fluctuations in the energy released, leading to the variability observed in many objects. The broadening of the spectral lines observed in the nuclei of many active galaxies results from the rapid orbital motion of the gas in the black hole's intense gravity.

Jets appear to be a common feature of accretion flows, large and small, and consist of material (mainly protons and electrons) blasted out into space—and completely out of the visible portion of the galaxy—from the inner regions of the disk. They are most likely formed by strong magnetic fields produced within the accretion disk itself, which accelerate charged particles to nearly the speed of light and eject them parallel to the disk's rotation axis. Figure 15.31 shows a *Hubble Space Telescope* image of a disk of gas and dust at the core of the radio galaxy NGC 4261 in the Virgo Cluster. Consistent with the theory just described, the disk is perpendicular to the huge jets emanating from the galaxy's center.

Figure 15.32 shows further evidence for this model in the form of imaging and spectroscopic data from the center of M87, suggesting a rapidly rotating disk of matter orbiting the galaxy's center, again perpendicular to the jet. Measurements of the gas velocity on opposite sides of the disk indicate that the mass within a few parsecs of the center is approximately 3×10^9 solar masses—we assume that this is the mass of the central black hole.

CONCEPT CHECK

How does accretion onto a supermassive black hole power the energy emission from the extended radio lobes of a radio galaxy?



▶ **FIGURE 15.31 Giant Elliptical Galaxy** (a) A combined optical/radio image of the giant elliptical galaxy NGC 4261, in the Virgo Cluster, shows a white visible galaxy at center, from which blue-orange (false color) radio lobes extend for about 60 kpc. (b) A close-up of the galaxy's nucleus reveals a 100-pc-diameter disk surrounding a bright hub thought to harbor a black hole. *(NRAO; NASA)*

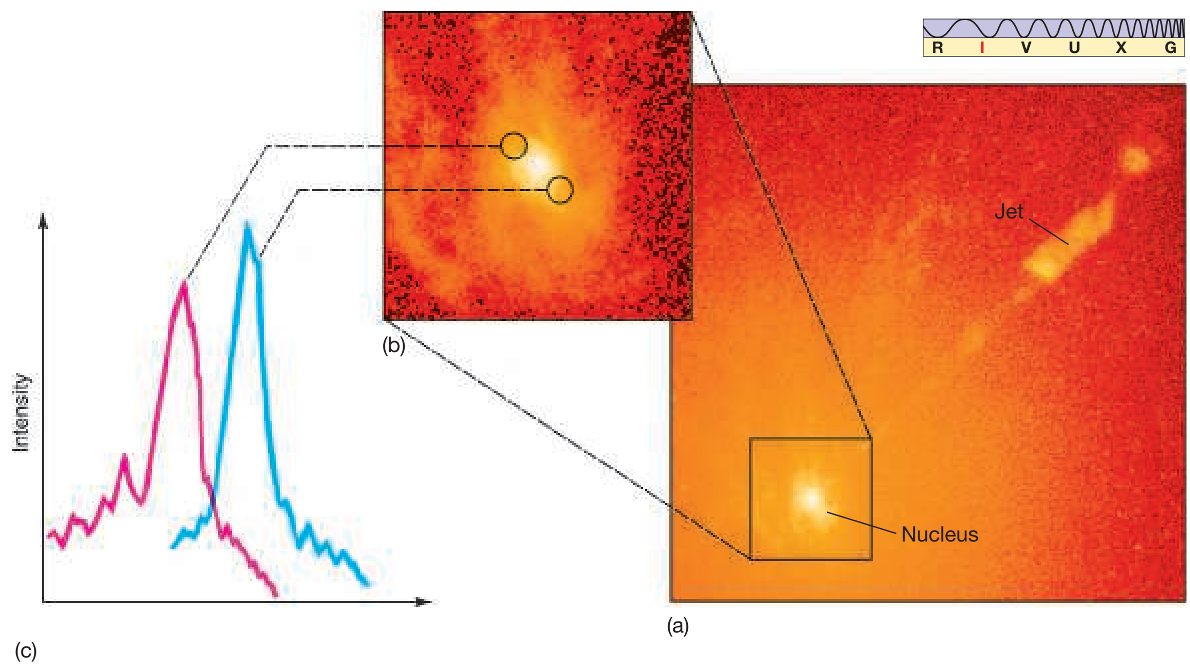
Energy Emission

The radiation emitted by the hot accretion disk surrounding a supermassive black hole spans a broad range of wavelengths, from infrared through X-rays, corresponding to the broad range of gas temperatures in the disk. This accounts for the spectra of some active galactic nuclei, but as mentioned earlier, it appears that in many cases the high-energy radiation emitted from the accretion disk itself is "reprocessed"—that is, absorbed and reemitted at infrared wavelengths—by dust surrounding the nucleus before eventually reaching our detectors.

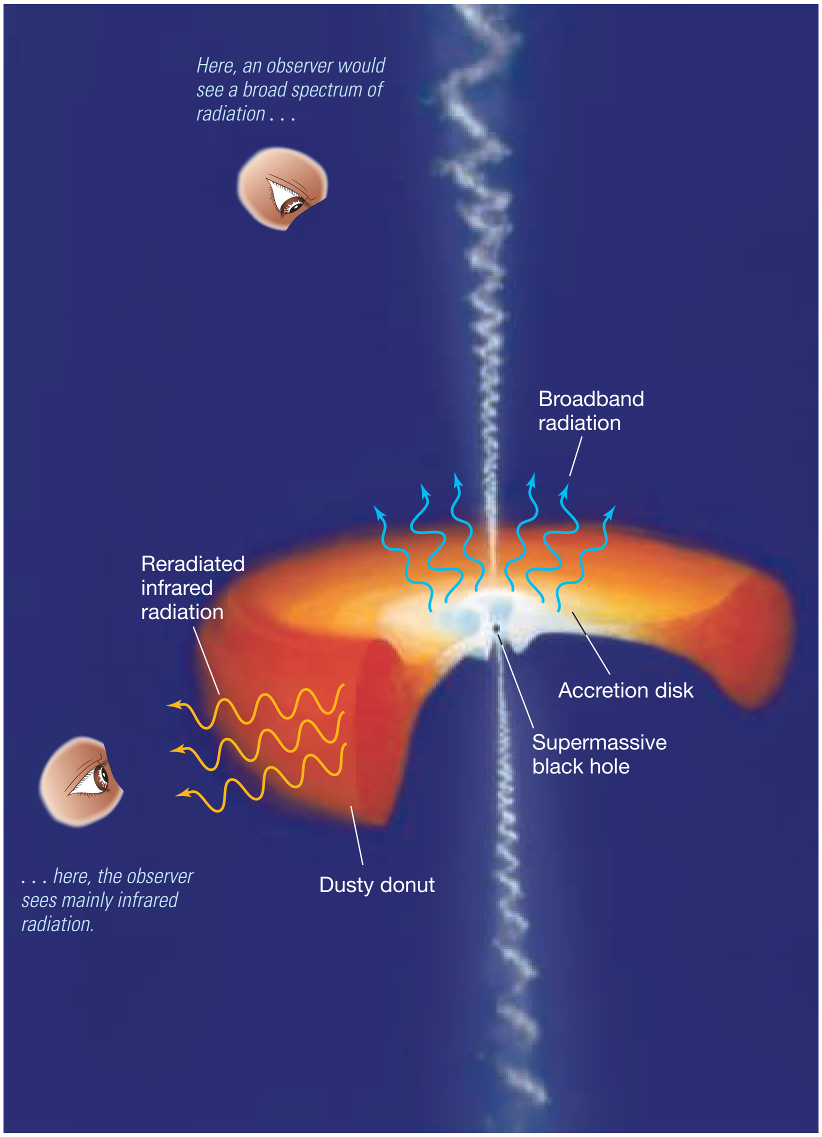
Many researchers think that the most likely site of this reprocessing is in a rather fat, donut-shaped ring of gas and dust surrounding the inner accretion disk where the energy is actually produced. As illustrated in Figure 15.33, if our line of sight to the black hole does not intersect the dusty donut, we see the "bare" energy source, emitting large amounts of high-energy radiation. If the donut intervenes, we see instead large amounts of infrared radiation reradiated from the dust. The structure of the donut itself is quite uncertain and may in reality bear little resemblance to the rather regular-looking ring shown in the figure. Some astronomers prefer a different explanation: If quasars, like stars are born shrouded in dense gas, then the difference between "reprocessed" and "bare" systems may be an evolutionary one, as the radiation from the obscured disk disperses its surrounding cocoon and bursts into view. ∞ *(Sec. 11.2)*

A different reprocessing mechanism operates in many jets and radio lobes. It involves the *magnetic fields* possibly produced within the accretion disk and transported by the jets into intergalactic space (Figure 15.30). As sketched in Figure 15.34(a), whenever a charged particle (here an electron) encounters a magnetic field, the particle tends to spiral around the magnetic field lines. We have already encountered this idea on smaller scales in Earth's magnetosphere and at the center of our own Galaxy. ∞ *(Sec.5.7, 9.4, 13.2, 14.7)*

As the particles whirl around, they emit electromagnetic radiation. ∞ *(Sec. 2.2)* The radiation produced in this way—called **synchrotron radiation**, after the type



▶ **FIGURE 15.32 M87 Disk** Both images and spectra of M87 support the idea of a rapidly whirling accretion disk at this galaxy's heart. (a) The central region of M87, similar to that shown in Figure 15.26(c), shows its bright nucleus and jet. (b) A magnified view of the nucleus implies a spiral swarm of stars, gas, and dust. (c) Spectral-line features observed on opposite sides of the nucleus show contrasting red and blue Doppler shifts, implying that matter on one side is coming toward us while matter on the other side is moving away. Apparently, an accretion disk spins perpendicular to the jet, and at its center is a black hole having some three billion times the mass of the Sun. *(NASA)*



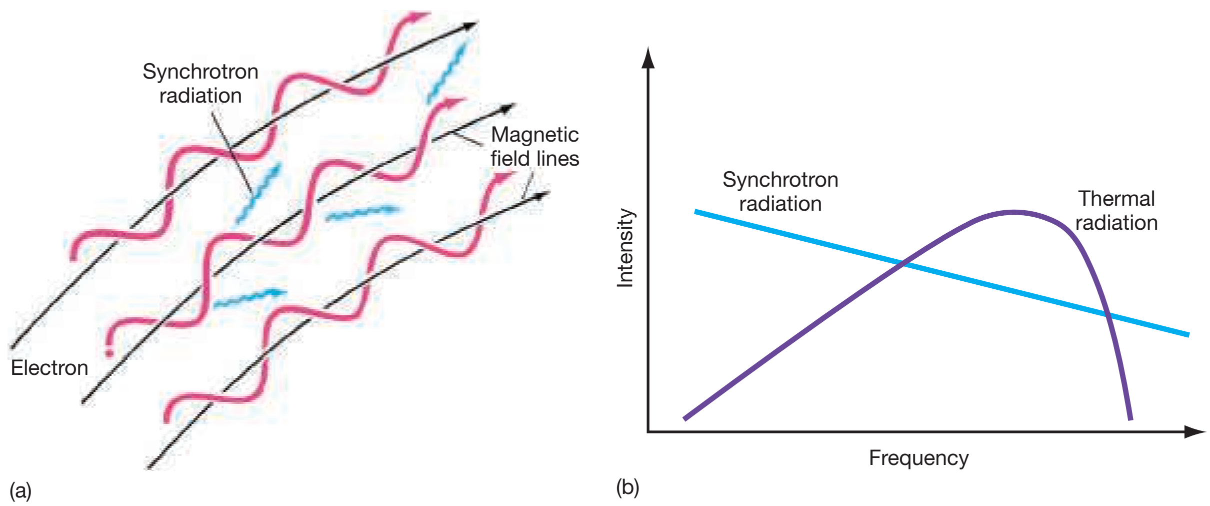
◀ **FIGURE 15.33 Dusty Donut** The accretion disk surrounding a massive black hole, drawn here with some artistic license, consists of hot gas at many different temperatures (hottest nearest the center). When viewed from above or below, the disk radiates a broad spectrum of electromagnetic energy extending into the X-ray band. However, the dusty infalling gas that ultimately powers the system is thought to form a fat, donut-shaped region outside the accretion disk (shown here in red), which effectively absorbs much of the high-energy radiation reaching it, reemitting it mainly in the form of cooler, infrared radiation. When the accretion disk is viewed from the side, strong infrared emission is observed. (Compare with Figure 15.25).

of particle accelerator in which it was first observed—is *nonthermal* in nature—the emitted radiation is not described, even approximately, by a blackbody curve. Instead, its intensity decreases with increasing frequency, as shown in Figure 15.34(b). This is just what is needed to explain the overall spectrum of radiation from many active galaxies. Observations of the radiation received from the jets and radio lobes of active galaxies are completely consistent with this process.

Eventually, the jet is slowed and stopped by the intergalactic medium, the flow becomes turbulent, and the magnetic field grows tangled. The result is a gigantic radio lobe emitting virtually all of its energy in the form of synchrotron radiation. Thus, even though the radio *emission* comes from an enormously extended volume of space that dwarfs the visible galaxy, the *source* of the energy is still the accretion disk—a billion billion times smaller in volume than the radio lobe—lying at the galactic center. The jets transport energy from the nucleus, where it is generated, into the lobes, where it is finally radiated into space.

The existence of the inner lobes of Centaurus A and the blobs in M87's jet imply that the formation of a jet may be an intermittent process (or, as in the case of the Seyferts discussed earlier, may not occur at all). Many nearby active galaxies (like Centaurus A) appear to have been "caught in the act" of interacting with another galaxy, suggesting that the fuel supply can be "turned on" by a companion.

We will explore further the connection between normal and active galaxies in Chapter 16, where we turn to the subject of *galaxy evolution*.



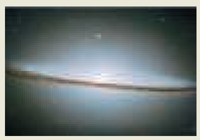
▶ **FIGURE 15.34 Nonthermal Radiation** (a) Charged particles, especially fast-moving electrons (red), emit synchrotron radiation (blue) while spiraling in a magnetic field (black). Thermal and synchrotron (nonthermal) radiation vary differently with frequency. Thermal radiation, described by a blackbody curve, peaks at a frequency that depends on the temperature of the source. By contrast, nonthermal synchrotron radiation (b) is more intense at low frequencies and is independent of the temperature of the emitting object. (Compare with Figure 15.18.)

THE BIG QUESTION

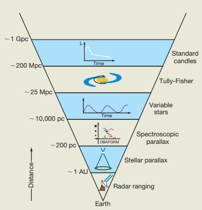
Galactic research lags stellar research by about 50 years. That's because galaxies were discovered only in the 20th century, and we are still learning about them. How did they form, and how do they evolve? Those are the biggest questions regarding galaxies, and they will not be answered until more and better data accumulate, especially regarding the most distant systems. Will the much larger galaxy surveys now on the horizon help solve these important issues?

CHAPTER REVIEW

SUMMARY

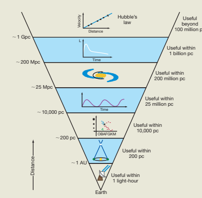


LO1 The **Hubble classification scheme** (p. 420) divides galaxies into several classes, depending on their appearance. **Spiral galaxies** (p. 421) have flattened disks, central bulges, and spiral arms. Their halos consist of old stars, whereas the gas-rich disks are the sites of ongoing star formation. **Barred-spiral galaxies** (p. 422) contain an extended "bar" of material projecting beyond the central bulge. **Elliptical galaxies** (p. 422) have no disk and contain little or no cool gas or dust, although very hot interstellar gas is observed. In most cases, they consist entirely of old stars. They range in size from dwarf ellipticals, which are much less massive than the Milky Way Galaxy, to giant ellipticals, which may contain trillions of stars. **S0** and **SB0 galaxies** (p. 423) are intermediate in their properties between ellipticals and spirals. **Irregular galaxies** (p. 424) are galaxies that do not fit into either of the other categories. Some may be the result of galaxy collisions or close encounters. Many irregulars are rich in gas and dust and are the sites of vigorous star formation.

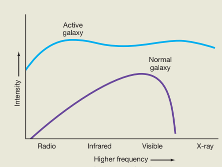


LO2 Astronomers often use **standard candles** (p. 426) as distance-measuring tools. These are objects that are easily identifiable and whose luminosities lie in some reasonably well-defined range. Comparing luminosity and apparent brightness, astronomers determine the distance using the inverse-square law. An alternative approach is the **Tully–Fisher relation** (p. 427), an empirical correlation between rotational velocity and luminosity in spiral galaxies.

LO3 The Milky Way, Andromeda, and several other smaller galaxies form the **Local Group** (p. 428), a small **galaxy cluster** (p. 429). Galaxy clusters consist of a collection of galaxies orbiting one another, bound together by their own gravity. The nearest large galaxy cluster to the Local Group is the Virgo Cluster.



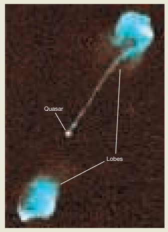
LO4 Distant galaxies are observed to be receding from the Milky Way at speeds proportional to their distances from us. This relationship is called **Hubble's law** (p. 430). The constant of proportionality in the law is **Hubble's constant** (p. 431). Its value is approximately 70 km/s/Mpc. Astronomers use Hubble's law to determine distances to the most remote objects in the universe simply by measuring their redshifts and converting the corresponding speed directly to a distance. The redshift associated with the Hubble expansion is called the **cosmological redshift** (p. 431).



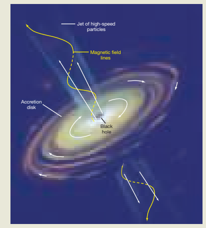
LO5 **Active galaxies** (p. 432) are much more luminous than normal galaxies and have nonstellar spectra, emitting most of their energy outside the visible part of the electromagnetic spectrum. Often the nonstellar activity suggests rapid internal motion and is associated with a bright central **active galactic nucleus** (p. 433). Many active galaxies have high-speed, narrow jets of matter shooting out from their central nuclei. Often the jets transport energy from

the nucleus, where it is generated, to enormous **radio lobes** (p. 434) lying far beyond the visible portion of the galaxy, where it is radiated into space. The jets often appear to be made up of distinct "blobs" of gas, suggesting that the process generating the energy is intermittent.

LO6 A **Seyfert galaxy** (p. 433) looks like a normal spiral, except that the Seyfert has an extremely bright central **galactic nucleus** (p. 433). Spectral lines from Seyfert nuclei are very broad, indicating rapid internal motion, and rapid variability implies that the source of the radiation is much less than 1 light-year across. **Radio galaxies** (p. 434) emit large amounts of energy in the radio part of the spectrum. The corresponding visible galaxy is usually elliptical. **Quasars** (p. 439), or **quasi-stellar objects** (p. 439), are the most luminous objects known. In visible light they appear starlike, and their spectra are usually substantially redshifted. All quasars are very distant, indicating that we see them as they were in the distant past.



LO7 The generally accepted explanation for the observed properties of all active galaxies is that the energy is generated by accretion of galactic gas onto a supermassive (million- to billion-solar-mass) black hole lying in the galactic center. The small size of the accretion disk explains the compact extent of the emitting region, and the high-speed orbit of gas in the black hole's intense gravity accounts for the rapid motion observed. Much of the high-energy radiation emitted from the disk is absorbed by a fat, donut-shaped region outside the disk and reemitted in the form of infrared radiation. Typical active galaxy luminosities require the consumption of about 1 solar mass of material every few years. Some of the infalling matter is blasted out into space, producing magnetized jets that create and feed the radio lobes. Charged particles spiraling around the magnetic field lines produce **synchrotron radiation** (p. 441), whose spectrum is consistent with the nonstellar radiation observed in radio galaxies and jets.



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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 Distinguish among the various types of spiral galaxies.
2. Compare an elliptical galaxy with the halo of the Milky Way.
3. LO2 Describe the four rungs in the distance-measurement ladder involved in determining the distance to a galaxy lying 5 Mpc away.
4. How does the Tully–Fisher relation allow astronomers to measure the distances to galaxies?
5. LO3 What is the Virgo Cluster?
6. LO4 What is Hubble's law, and how is it used by astronomers to measure distances to galaxies?
7. What is the most likely range of values for Hubble's constant?
8. Why do astronomers prefer to speak in terms of redshifts rather than distances to faraway objects?
9. LO5 Name two differences between normal and active galaxies.
10. LO6 POS What is the evidence that the radio lobes of some active galaxies consist of material ejected from the galaxy's nucleus?
11. POS How do we know that the energy-emitting regions of many active galaxies must be very small?
12. LO7 Briefly describe the leading model for the central engine of an active galaxy.
13. POS How do astronomers account for the differences in the spectra observed from active galaxies?
14. POS How is the process of synchrotron emission related to observations of active galaxies?
15. How do we know that quasars are extremely luminous?

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

1. Most galaxies are spirals like the Milky Way. (T/F)
2. Most elliptical galaxies contain only old stars. (T/F)
3. Irregular galaxies, although small, often have lots of star formation taking place in them. (T/F)
4. Type I supernovae can be used to determine distances to galaxies. (T/F)
5. Most galaxies are receding from the Milky Way Galaxy. (T/F)
6. Hubble's law can be used to determine distances to the farthest objects in the universe. (T/F)
7. Active galaxies can emit thousands of times more energy than our own Galaxy. (T/F)
8. Using the method of standard candles, we could, in principle, estimate the distance to a campfire if we knew (a) the number of logs used; (b) the fire's temperature; (c) the length of time the fire has been burning; (d) the type of wood used in the fire.
9. Within 30 Mpc of the Sun, there are about (a) 3 galaxies; (b) 30 galaxies; (c) a few thousand galaxies; (d) a few million galaxies.
10. Hubble's law states that (a) more distant galaxies are younger; (b) the greater the distance to a galaxy, the greater is the galaxy's redshift; (c) most galaxies are found in clusters; (d) the greater the distance to a galaxy, the fainter the galaxy appears.

11. If the light from a galaxy fluctuates in brightness very rapidly, the region producing the radiation must be (a) very large; (b) very small; (c) very hot; (d) rotating very rapidly.
12. Quasar spectra (a) are strongly redshifted; (b) show no spectral lines; (c) look like the spectra of stars; (d) contain emission lines from unknown elements.
13. Active galaxies are very luminous because they (a) are hot; (b) contain black holes in their cores; (c) are surrounded by hot gas; (d) emit jets.
14. VIS If the galaxy in Figure 15.10 (Galaxy Rotation) were smaller and spinning more slowly, then the figure should be redrawn to show (a) a greater blueshift; (b) a greater redshift; (c) a narrower combined line; (d) a larger combined amplitude.
15. VIS According to Figure 15.18 (Galaxy Energy Spectra), active galaxies (a) emit most of their energy at long wavelengths; (b) emit very little energy at high frequencies; (c) emit large amounts of energy at all wavelengths; (d) emit most of their energy in the visible part of the spectrum.

PROBLEMS

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

1. ■ The Andromeda galaxy lies 800 kpc from our Galaxy and is approaching it with a radial velocity of 266 km/s. Neglecting both the transverse component of the velocity and the effect of gravity in accelerating the motion, estimate when the two galaxies will collide.
2. ■■ A Cepheid variable star in the Virgo Cluster has an apparent magnitude of 26 and is observed to have a pulsation period of 20 days. Use these numbers and Figure 14.6 to estimate the distance to the Virgo Cluster. The absolute magnitude of the Sun is +4.85.
3. ■ A supernova 1 billion times more luminous than the Sun is used as a standard candle to measure the distance to a faraway galaxy. From Earth, the supernova appears as bright as the Sun would appear from a distance of 10 kpc. What is the distance to the galaxy?
4. ■ According to Hubble's law, with, with H_0 = 70 km/s/Mpc, what is the recessional speed of a galaxy at a distance of 200 Mpc? How far away is a galaxy whose recessional speed is 4000 km/s? How would these answers change if (a) H_0 = 50 km/s/Mpc, (b) H_0 = 80 km/s/Mpc?
5. ■■ If H_0 = 70 km/s/Mpc, how long will it take for the distance from the Milky Way Galaxy to the Virgo Cluster to double? How long for the distance to the Coma Cluster (100 Mpc) to double?
6. ■■ A quasar is observed to have luminosity fluctuations and broadened emission lines indicating a speed of 5000 km/s within 0.1 light-years of its center. Assuming circular orbits, use Kepler's laws to estimate the mass within this radius. ∞ *(Sec. 14.6)*
7. ■ Assuming a jet speed of 75 percent of the speed of light, calculate the time taken for material in Cygnus A's jet to cover the 250 kpc between the galaxy's nucleus and its radio-emitting lobes.
8. ■■ Assuming the upper end of the efficiency range indicated in the text, calculate how much energy an active galaxy would generate if it consumed one Earth mass of material every day. Compare this value with the luminosity of the Sun.
9. ■ Using the data presented in the text, calculate the orbital speed of material orbiting at a distance of 0.25 pc from the center of M87.
10. ■■■ Calculate the amount of energy received per unit area per unit time that would be observed at Earth from a 10^{37}-W Seyfert nucleus located at the Galactic center, 8 kpc away, neglecting the effects of absorption by interstellar dust. Using the data presented in Appendix 3, Table 3, compare this with the energy received from Sirius A, the brightest star in the night sky. From what you know about active galaxy energy emission, is it reasonable to ignore interstellar absorption?

ACTIVITIES

Collaborative

1. Observe the Virgo Cluster of galaxies. An 8-inch telescope is the optimal size for this project. The constellation Virgo is visible from the United States during much of fall through spring. To locate the cluster, first find the constellation Leo. The eastern part of Leo is composed of a distinct triangle of stars, Denebola (β), Chort (θ), and Zosma (δ). Go from Chort to Denebola in a straight line east; continue on the same distance as between the two stars, and you will be approximately at the center of the Virgo Cluster. Look for the following Messier objects, the brightest galaxies in the cluster: M49, M58, M59, M60, M84, M86, M87, M89, and M90. Examine each galaxy for unusual features; some have very bright nuclei. Sketch or photograph what you see, and construct your own pictorial catalog of the brightest galaxies in Virgo.

Individual

1. In the previous exercise, you were given directions for finding the Virgo Cluster of galaxies. M87, in the central part of this cluster, is the nearest core–halo radio galaxy. M87 has coordinates RA = $12^h\ 30.8^m$, dec = +12° 24′. At magnitude 8.6 it should not be difficult to find with an 8-inch telescope. Its distance is roughly 18 Mpc. Describe its nucleus; compare what you see with other nearby ellipticals in the Virgo Cluster.
2. 3C 273 is the nearest and brightest quasar, but that does not mean it is easy to find! Its coordinates are RA = $12^h\ 29.2^m$, dec = +2° 03′. It is located in the southern part of the Virgo Cluster, but it is not associated with it. At magnitude 12–13 (again, it is variable), it may require a 10- or 12-inch telescope to see, but try it first with an 8-inch. It should appear as a very faint star. The significance of seeing this object is that it is 640 Mpc distant. The light you are seeing left this object over 2 billion years ago! It is the most distant object observable with a small telescope.

16

Galaxies and Dark Matter

The Large-Scale Structure of the Cosmos

On scales much larger than even the largest galaxy clusters, new levels of structure are revealed, and a humbling new reality emerges. We may be star stuff, the product of countless cycles of stellar evolution, but we are not the stuff of the cosmos. The universe in the large is composed of matter fundamentally different from the familiar atoms and molecules that compose our bodies, our planet, our star and galaxy, and all the luminous matter we observe in the heavens. Only its gravity announces the presence of this strange kind of matter. By comparing and classifying the properties of galaxies near and far, astronomers have begun to understand their evolution. By mapping out their distribution in space, astronomers trace out the immense realms of the universe. Points of light in the uncharted darkness, the galaxies remind us that our position in the universe is no more special than that of a boat adrift at sea.

THE BIG PICTURE

Galaxies are among the grandest, most beautiful objects in the universe—each one a colossal collection of hundreds of billions of stars held together loosely by gravity. Galaxies dominate our view of deep space—they seem to be everywhere—yet they represent just a tiny fraction of all matter in the cosmos. Vast quantities of unseen cosmic material—dark matter—actually account for most of the mass in the universe.

◄ Galaxies are among the grandest, most beautiful objects in the universe—each one a colossal collection of hundreds of billions of stars held together loosely by gravity. Some are bright and splendid, like the two big ones in this image. Others are dim and distant, like several that appear smaller in the background. This pair of galaxies, nearly 300 million light-years away and known collectively as Arp 273, is in the process of colliding over millions of years. Notice the rose-like shape of the top galaxy, caused by the gravitational pull of the bottom one, and the swath of clusters of young blue stars glowing like jewels. Mergers and acquisitions are apparently common among galaxies, but astronomers still don't understand well how the galaxies originated long ago. *(STScI)*

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Describe some methods used to determine the masses of galaxies and galaxy clusters.
- **LO2** Explain why astronomers think that most of the matter in the universe is dark.
- **LO3** Describe how galaxies form and evolve, and outline the role of collisions in the process.
- **LO4** Present the evidence for supermassive black holes in the centers of galaxies, and explain how active galaxies fit into current theories of galactic evolution.
- **LO5** Describe how galaxies are distributed on large scales in the universe.
- **LO6** Outline some techniques used by astronomers to probe the universe on very large scales.

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16.1 Dark Matter in the Universe

In Chapter 14 we saw how measurements of the orbital velocities of stars and gas in our Galaxy reveal the presence of an extensive *dark-matter halo* surrounding the galaxy we see. (Sec. 14.6) Do other galaxies have similar dark halos? And what evidence do we have for dark matter on larger scales? To answer these questions, we need to know the masses of galaxies and galaxy clusters.

INTERACTIVE MA
Rotation Curve for a Merry-Go-Round

How can we measure the masses of such large systems? Surely, we can neither count all their stars nor estimate their interstellar content very well. Galaxies are just too complex to take direct inventory of their material makeup. Instead, we must rely on indirect techniques. Despite their enormous sizes, galaxies and galaxy clusters obey the same physical laws as do the planets in our own solar system. To determine galaxy masses, we turn as usual to Newton's law of gravity.

ANIMATION/VIDEO MA
Dark Matter

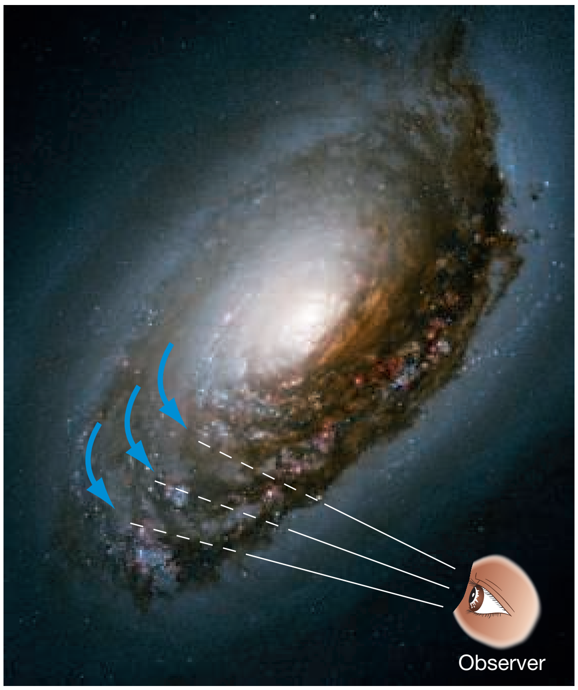
Galaxy Masses

Astronomers can determine the masses of some spiral galaxies by measuring their *rotation curves*, which plot rotation speed versus distance from the galactic center (Figure 16.1a). (Sec. 14.6) The mass within any given radius then follows directly from Newton's laws. Rotation curves for a few nearby spirals are shown in Figure 16.1(b). They imply masses ranging from about 10^{11} to 5×10^{11} solar masses within about 25 kpc of the center—comparable to the results obtained for our own Galaxy using the same technique. For galaxies too distant for detailed rotation curves to be drawn, the overall rotation speed can still be inferred from the broadening of spectral lines, as described in the previous chapter. (Sec. 15.2)

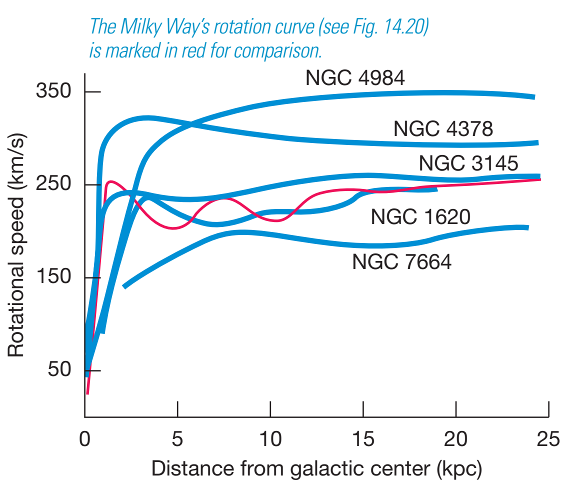
This approach is useful for measuring the mass lying within about 50 kpc of a galaxy's center (the extent of the electromagnetic emission from stellar and interstellar material). To probe farther from the centers of galaxies, astronomers turn to *binary* galaxy systems (Figure 16.2a), whose components may lie hundreds of kiloparsecs apart. The orbital period of such a system is typically billions of years, far too long for the orbit to be accurately measured. However, by estimating the period and semimajor axis using the information available—the line-of-sight velocities and angular separation of the components—an approximate total mass can be derived. (Sec. 1.4)

Galaxy masses obtained in this way are fairly uncertain, but by combining many such measurements, astronomers can obtain quite reliable *statistical* information about galaxy masses. Most normal spirals (the Milky Way Galaxy included) and large ellipticals contain between 10^{11} and 10^{12} solar masses of material. Irregular galaxies often contain less mass, about 10^8 to 10^{10} times that of the Sun. Dwarf ellipticals and dwarf irregulars can contain as little as 10^6 or 10^7 solar masses of material.

We can use another statistical technique to derive the combined mass of all the galaxies within a galaxy cluster. As depicted in Figure 16.2(b), each galaxy within a cluster moves relative to all other cluster members, and we can estimate the cluster's mass simply by asking how massive it must be in order to bind its galaxies gravitationally. Typical cluster masses obtained in this way lie in the range of 10^{13}–10^{14} solar masses. Notice that this calculation gives us no information whatsoever about the masses of individual galaxies. It tells us only about the *total* mass of the entire cluster.



(a)



(b)

◀ **FIGURE 16.1 Galaxy Rotation Curves** INTERACTIVE (a) Orbital velocities can be measured at different distances from the center of a disk galaxy, as illustrated here for M64, the "Evil Eye" galaxy, some 5 Mpc distant. (b) Rotation curves for some nearby spiral galaxies indicate masses of a few hundred billion times the mass of the Sun. *(NASA)*

Visible Matter and Dark Halos

The rotation curves of the spiral galaxies shown in Figure 16.1(b) remain flat (that is, do not decline and may even rise slightly) far beyond the visible images of the galaxies themselves, implying that these galaxies—and perhaps all spiral galaxies—have invisible dark halos similar to that surrounding the Milky Way. *(Sec. 14.5)* Spiral galaxies seem to contain from 3 to 10 times more mass than can be accounted for in the form of visible matter. Studies of elliptical galaxies suggest similarly large dark halos surrounding those galaxies, too.

Astronomers find even greater discrepancies between visible light and total mass when they study galaxy clusters. Calculated cluster masses range from 10 to nearly 100 times the mass suggested by the light emitted by individual cluster galaxies. Put another way, a lot more mass is needed to bind galaxy clusters than we can see. Thus, the problem of dark matter exists not just in our own Galaxy, but also in other galaxies and, to an even greater degree, in galaxy clusters, too. In that case, we are compelled to accept the fact that *upward of 90 percent of the matter in the universe is dark*. As noted in Chapter 14, this matter is not just dark in the visible portion of the spectrum—it is undetected at *any* electromagnetic wavelength. *(Sec. 14.5)*

The dark matter in clusters is not simply the accumulation of dark matter within individual galaxies. Even including the galaxies' dark halos, we still cannot account for all the dark matter in galaxy clusters. As we look on larger and larger scales, we find that a larger and larger fraction of the matter in the universe is dark.

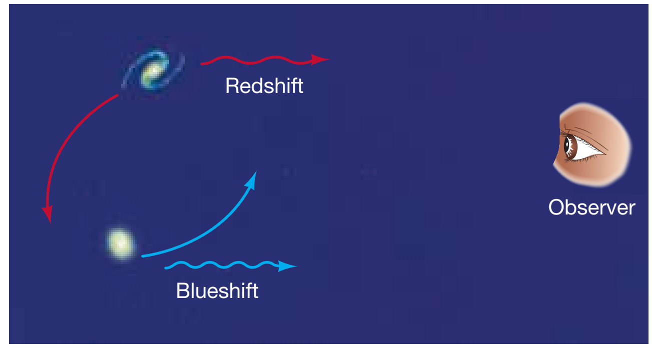
Intracluster Gas

In addition to the luminous matter observed within the cluster galaxies themselves, astronomers also have evidence for large amounts of *intracluster gas*—superhot (more than 10 million K), diffuse intergalactic matter filling the space among the galaxies. Satellites orbiting above Earth's atmosphere have detected X-rays from hot gas in many clusters. *(Sec. 3.5)* Figure 16.3 shows false-color X-ray images of two such systems. In each case, the X-ray–emitting region is centered on, and comparable in size to, the visible cluster image.

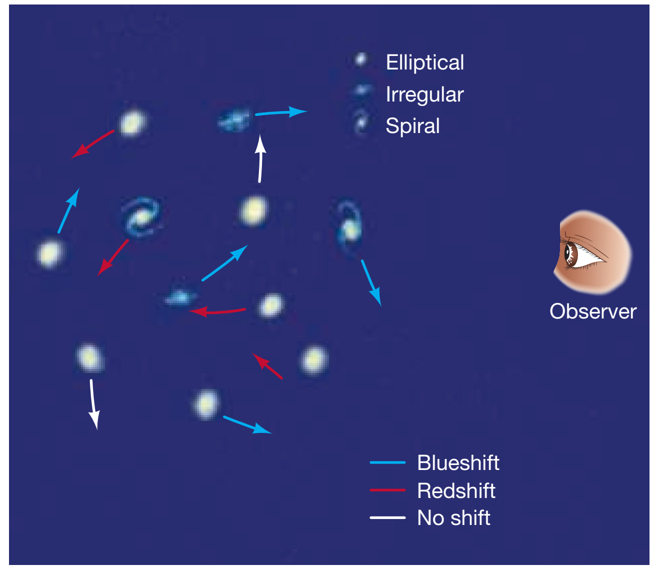
Further evidence for intracluster gas can be found in the appearance of the radio lobes of some active galaxies. *(Sec. 15.4)* In some systems, known as *head–tail* radio galaxies, the lobes seem to form a "tail" behind the main part of the galaxy. For example, the lobes of radio galaxy NGC 1265, shown in Figure 16.4, appear to be "swept back" by some onrushing wind, and, indeed, this is the most likely explanation for the galaxy's appearance. If NGC 1265 were at rest, it would be just another double-lobe source, perhaps quite similar to Centaurus A (see Figure 15.22). However, the galaxy is traveling through the intergalactic medium of its parent galaxy cluster (known as the Perseus Cluster), and the outflowing matter forming the lobes tends to be left behind as NGC 1265 moves.

How much gas do these observations reveal? At least as much matter—and in a few cases substantially more—exists within clusters in the form of hot gas as is visible in the form of stars. This is a lot of material, but it still doesn't solve the dark-matter problem. To account for the total masses of galaxy clusters implied by dynamical studies, we would have to find from 10 to 100 times more mass in gas than in stars.

Why is the intracluster gas so hot? Simply because its particles are bound by gravity and hence are moving at speeds comparable to those of the galaxies in the cluster—1000 km/s or so. Since temperature is just a measure of the speed at which the gas particles move, this speed translates (for protons, which make up the bulk of the mass) to a temperature of 40 million kelvins. *(More Precisely 5-1)*



(a)



(b)

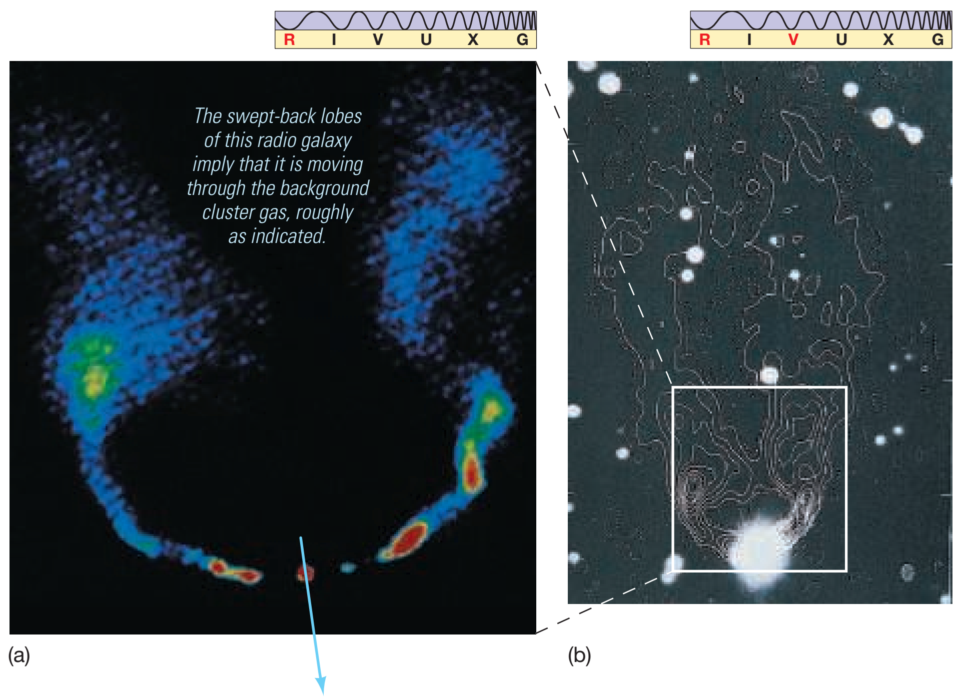
▲ **FIGURE 16.2 Galaxy Masses** (a) In a binary galaxy system, galaxy masses can be estimated by observing the orbit of one galaxy about the other. (b) The mass of a galaxy cluster can be estimated by observing the motion of many galaxies in the cluster and then estimating how much mass is needed to prevent the cluster from flying apart.

▶ **FIGURE 16.3** **Galaxy Cluster X-Ray Emission** The galaxy cluster Abell 1689 lies some 700 million parsecs from Earth. Its X-ray emission, shown here in blue, is superimposed on a *Hubble* image of the galaxies themselves, and shows clearly how the entire cluster is filled with hot, X-ray emitting gas. *(NASA)*

CONCEPT CHECK

What assumptions are we making when we infer the mass of a galaxy cluster from observations of the spectra of its constituent galaxies?

Where did the gas come from? There is so much of it that it could not have been expelled from the galaxies themselves. Instead, astronomers think that it is mainly *primordial*—gas that has been around since the universe began and that never became part of a galaxy. However, the intracluster gas does contain some heavy elements—carbon, nitrogen, and so on—implying that at least some of it is material ejected from galaxies after enrichment by stellar evolution. ∞ *(Sec. 12.7)* Just how this occurred remains a mystery.



▶ **FIGURE 16.4** **Head–Tail Radio Galaxy** (a) Radiograph, in false color, of the head–tail radio galaxy NGC 1265. (b) The same radio data, in contour form, superimposed on the optical image of the galaxy. *(NRAO; Palomar/Caltech)*

16.2 Galaxy Collisions

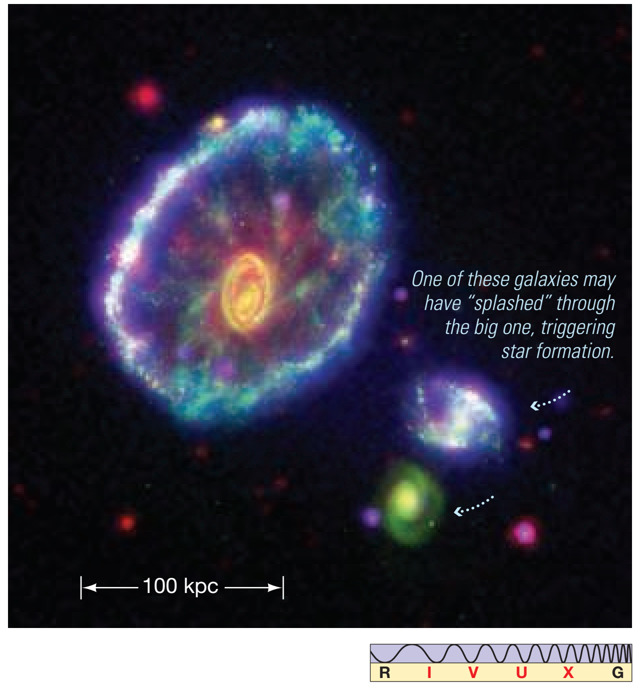
Contemplating the congested confines of a rich galaxy cluster (such as those shown in Figures 15.1 and 15.13) with thousands of member galaxies orbiting within a few megaparsecs, we might expect that collisions among galaxies would be common. ∞ *(Sec. 15.2)* Gas particles collide in our atmosphere, and hockey players collide in the rink. Do galaxies in clusters collide too? The answer is yes.

Figure 16.5 apparently shows the aftermath of a bull's-eye collision between a small galaxy (perhaps one of the two at the right, although that is by no means certain) and the larger galaxy at the left. The result is the Cartwheel Galaxy, about 150 Mpc from Earth, its halo of young stars resembling a vast ripple in a pond. The ripple is most likely a density wave created by the passage of the smaller galaxy through the disk of the larger one. ∞ *(Sec. 14.5)* The disturbance is now spreading outward from the region of impact, creating new stars as it goes.

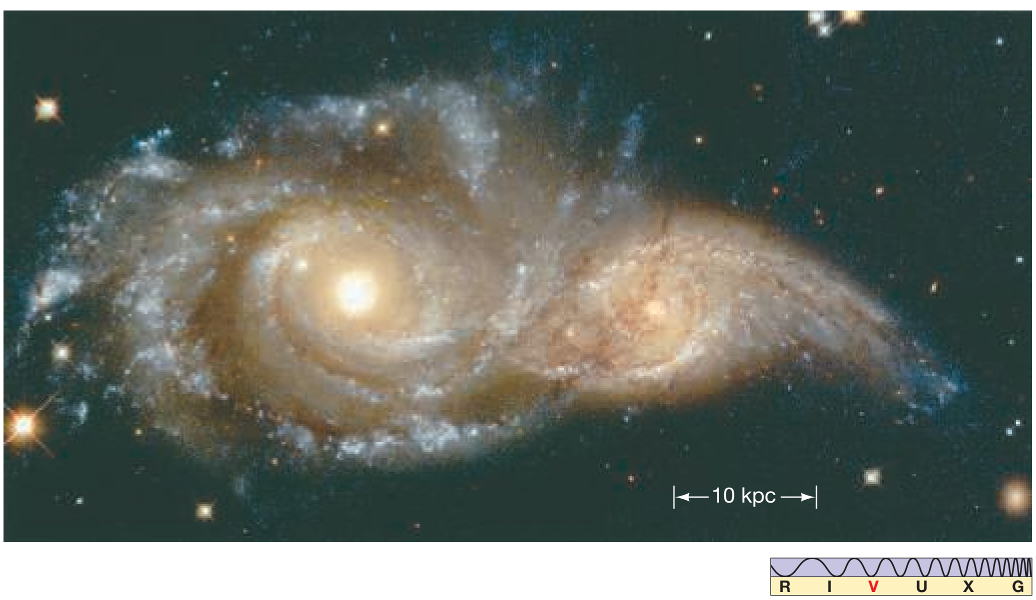
Figure 16.6 shows an example of a close encounter that hasn't (yet) led to an actual collision. Two spiral galaxies are apparently passing each other like majestic ships in the night. The larger and more massive galaxy at the bottom is called NGC 2207; the smaller one at the top is IC 2163. Analysis of this image suggests that IC 2163 is now swinging past NGC 2207 in a counterclockwise direction, having made a close approach some 40 million years ago. The two galaxies seem destined to undergo further close encounters, as IC 2163 apparently does not have enough energy to escape the gravitational pull of NGC 2207. In roughly a billion years, these two galaxies will probably merge into a single, massive galaxy.

These examples illustrate how galaxy interactions—close encounters or actual collisions—can have dramatic consequences for the galaxies involved, especially on their interstellar gas. The rapidly varying gravitational forces during the interaction compress the gas, often resulting in a galaxy-wide episode of star formation. The result is called a **starburst galaxy**. Figure 16.7 shows several more starburst systems in the (relatively) nearby universe.

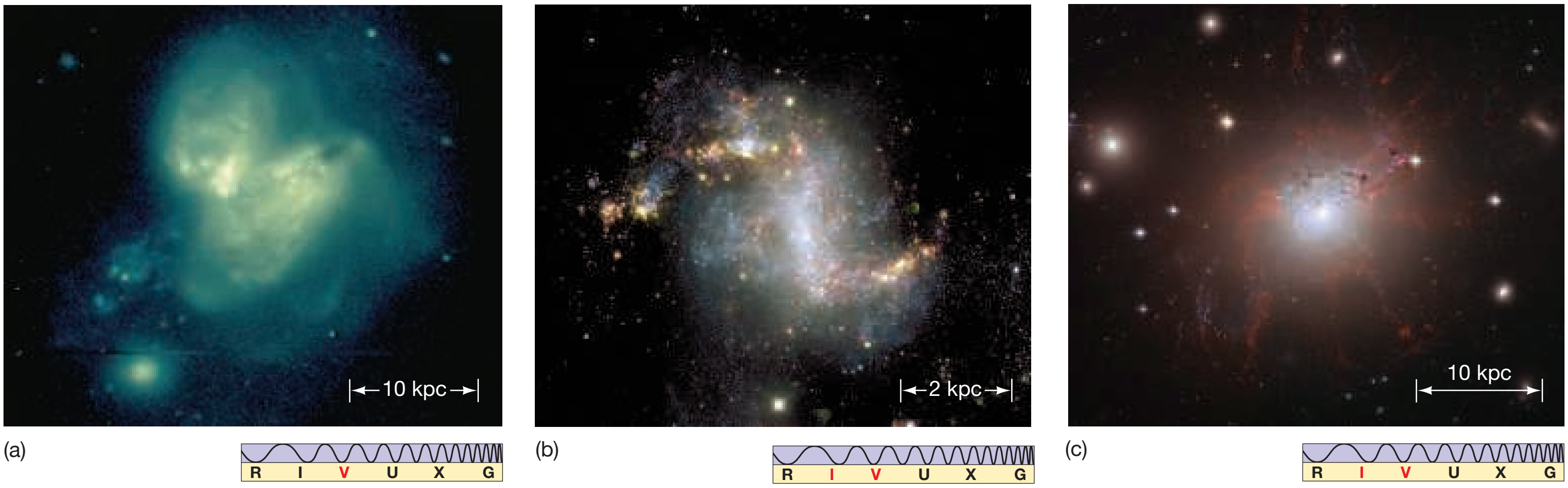
No human will ever witness an entire galaxy collision, for it lasts many millions of years. However, modern computers can follow the event in a matter of hours. Large-scale simulations modeling in detail the gravitational interactions among stars and gas, and incorporating the best available models of gas dynamics, allow astronomers to better understand the effects of a collision on the galaxies involved and even estimate the eventual outcome of the interaction. The



▲ **FIGURE 16.5 Cosmic Splash** The Cartwheel Galaxy (left) may have resulted from a collision (possibly with one of the smaller galaxies at right) that has led to an expanding ring of star formation moving outward through the galactic disk. This is a false color composite image combining four spectral bands: infrared in red (from *Spitzer*), optical in green (from *Hubble*), ultraviolet in blue (from *Galex*), and X-ray in purple (from *Chandra*). *(NASA)*



◀ **FIGURE 16.6 Galaxy Encounter** This encounter between two spiral galaxies, NGC 2207 (left) and IC 2163 (right), has already led to bursts of star formation in each. Eventually the two will merge, but not for a billion years or so. *(NASA)*



▲ **FIGURE 16.7 Starburst Galaxies** (a) This interacting galaxy pair (IC 694, at left, and NGC 3690) shows starbursts now under way in both galaxies—hence the bluish tint. (b) The galaxy NGC 1313 is experiencing a widespread burst of star formation, although the origin of that activiity is unclear. It currently seems to have no neighbors, but its asymmetric appearance and distorted halo outside the frame shown here suggest that it may have absorbed a smaller companion in the relatively recent past. (c) The peculiar (Irr II) active galaxy NGC 1275 contains a system of long filaments that seem to be exploding outward into space. The system was most likely formed by the collision of two galaxies. *(W. Keel; NASA)*

INTERACTIVE
Colliding Galaxies

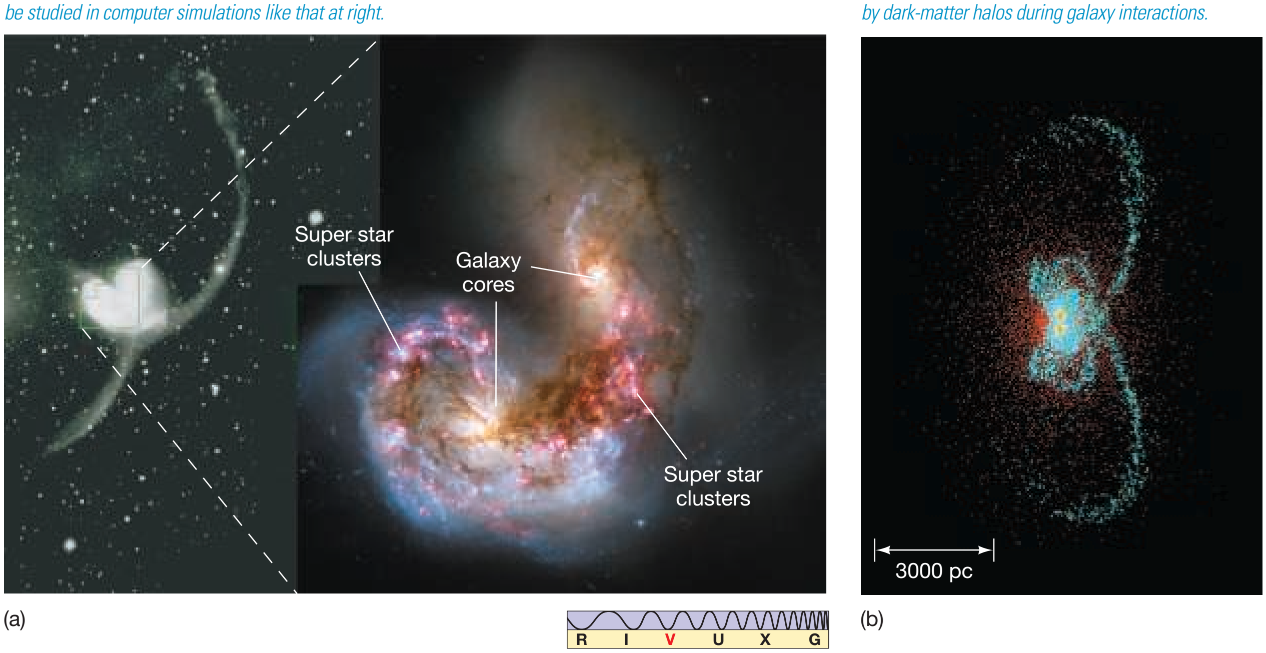
ANIMATION/VIDEO
Galaxy Collision I

computer simulation shown in Figure 16.8(b) began with two colliding spiral galaxies, not so different from those shown in Figure 16.6, but the details of the original structure have been largely obliterated by the collision. Notice the similarity to the real image of NGC 4038/4039 (Figure 16.8a), the so-called Antennae galaxies, which show extended tails, as well as double galactic centers only a few hundred parsecs across. Star formation induced by the collision is clearly traced by the blue light from thousands of young, hot stars and star clusters. The simulations indicate that, as with the galaxies in Figure 16.6, ultimately the two galaxies will merge into one.

Galaxies in clusters collide because their sizes are comparable to the distances between them—they simply don't have much room to roam around without bumping into one another. The large dark-matter halos surrounding many, if not all, galaxies are crucial to this process. These halos extend far beyond the visible galaxies, making them much larger than their optical appearance would suggest, greatly increasing the chances of interactions and mergers. Many researchers think that most galaxies in clusters have been strongly influenced by collisions, often in the relatively recent past.

Collisions seen in these real images at left can be studied in computer simulations like that at right.

Such simulations demonstrate the crucial role played by dark-matter halos during galaxy interactions.



▶ **FIGURE 16.8 Galaxy Collision** (a) The long tidal "tails" (black-and-white image at left) mark the final plunge of the "Antennae" galaxies a few tens of millions of years ago. Strings of young, bright "super star clusters" (magnified color image at center) were caused by violent shock waves produced in the gas disks of the two colliding galaxies. (b) A computer simulation of the encounter shows many of the same features as the real object at left. *(AURA; NASA; J. Barnes)*

Incidentally, we don't have to go far afield to find an example of an impending galaxy collision in a small cluster. Our nearest large neighbor, the Andromeda galaxy (see Figure 14.2), is currently approaching us at a velocity of about 120 km/s. In a few billion years it will collide with the Milky Way, and we will have an opportunity to see for ourselves up close what a galaxy collision is really like!

Curiously, although a collision may wreak havoc on the large-scale structure of the galaxies involved, it has essentially no effect on the individual stars they contain. The stars within each galaxy just glide past one another. In contrast to galaxies in the cluster, the stars in a galaxy are so small compared with the distances between them, that when two galaxies collide, the star population merely doubles for a time, and the stars continue to have so much space that they do not run into each other. Collisions can rearrange the stellar and interstellar contents of each galaxy, often producing a spectacular burst of star formation that may be visible to enormous distances, but from the point of view of the stars, it's clear sailing.

16.3 Galaxy Formation and Evolution

With Hubble's law as our guide to distances in the universe, and armed now with knowledge of the distribution of dark matter on galactic and larger scales, let's finally turn to the question of how galaxies came to be the way they are. Can we explain the different galaxy types we see? Astronomers know of no simple evolutionary connections among the various categories in the Hubble classification scheme. ∞ *(Sec. 15.1)* To answer the question, then, we must understand how galaxies formed.

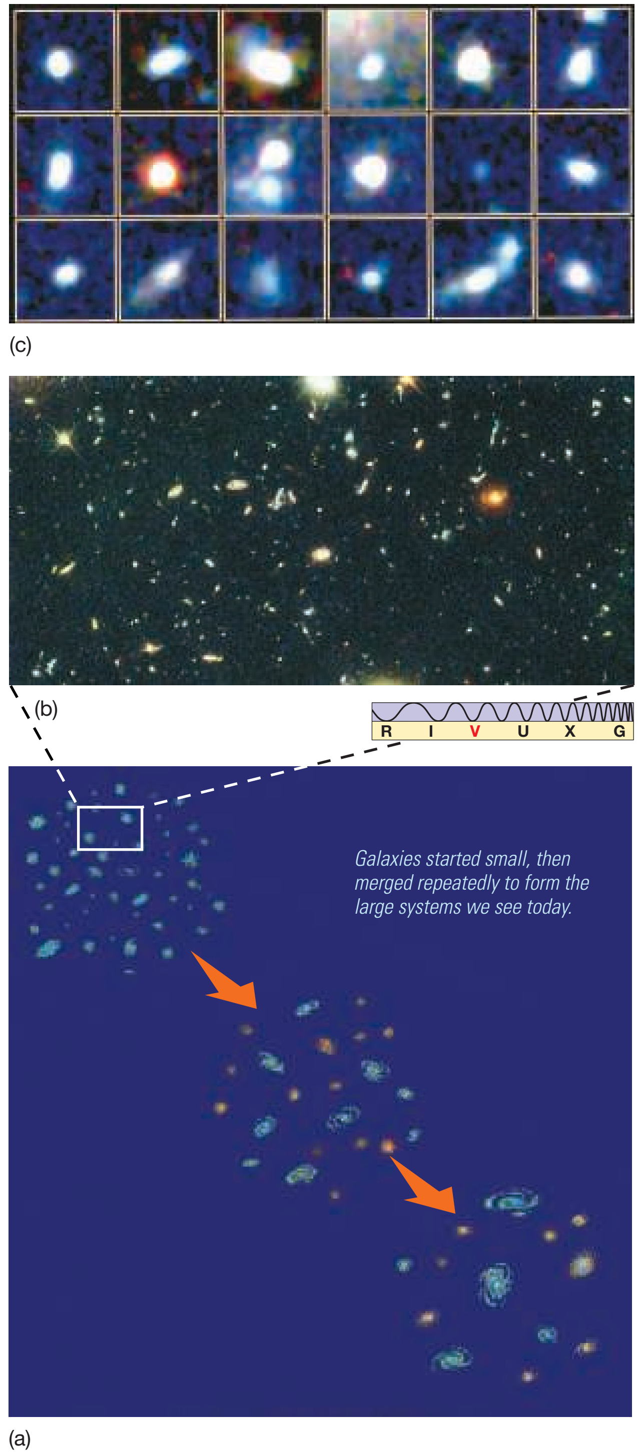
Unfortunately, compared with the theories of star formation and stellar evolution, the theory of galaxy formation is still very much in its infancy. Galaxies are much more complex than stars, they are harder to observe, and the observations are harder to interpret. More important, stars almost never *collide* with one another (apart from situations where stellar evolution causes binary components to merge), so most stars in galaxies evolve in isolation. ∞ *(Sec. 12.3)* Galaxies, however, may suffer numerous collisions during their lives, making it much harder to decipher their pasts. Indeed, collisions like those described in the previous section blur the distinction between formation and evolution, making it hard to separate one from the other.

Nevertheless, some general ideas have gained widespread acceptance, and we can offer some insights into the processes responsible for the galaxies we see. We first describe a general scenario for how large galaxies form from smaller ones, then discuss how galaxies change in time due to both internal stellar evolution and external influences. Finally, we consider how the galaxy types in Hubble's classification fit in to this broad picture.

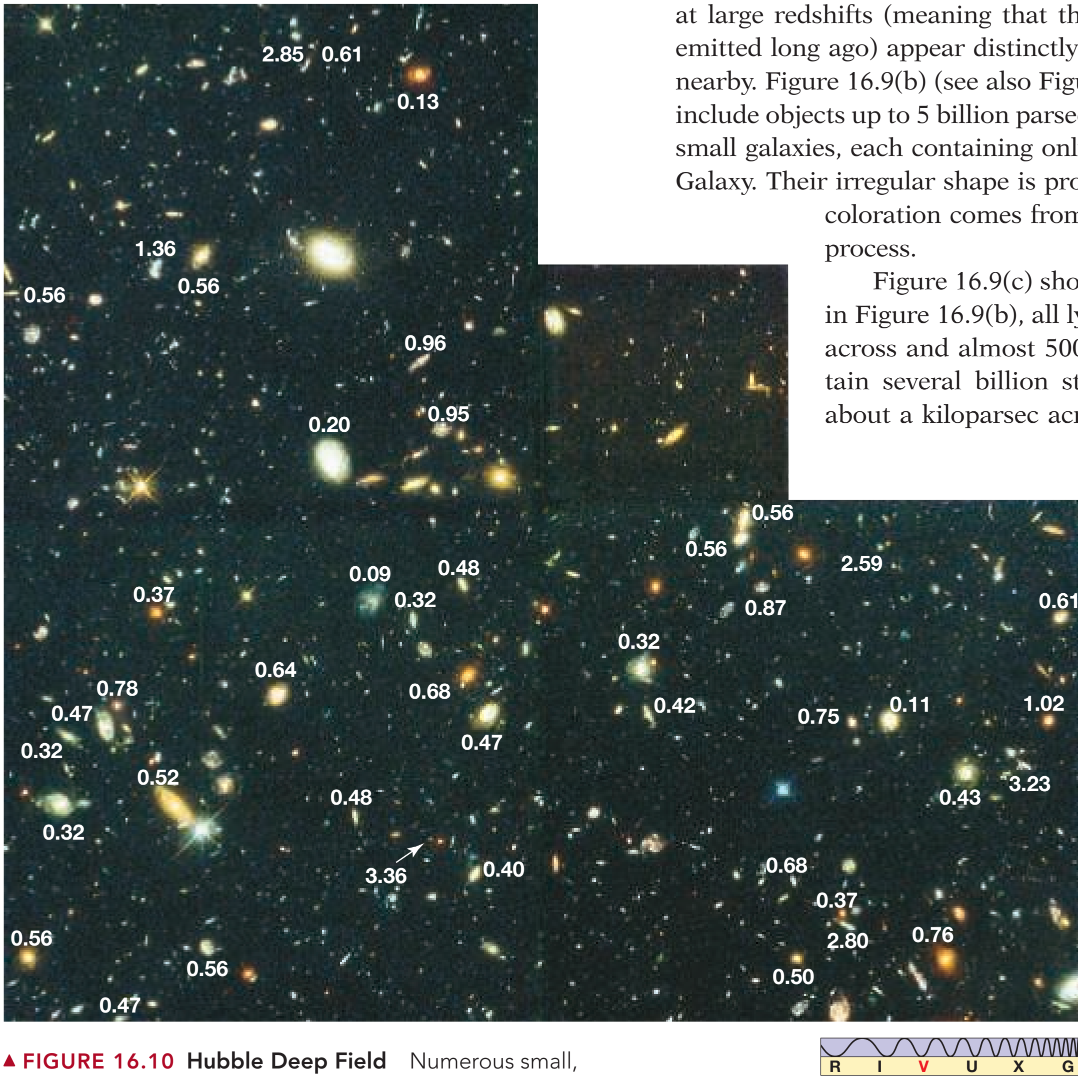
Mergers and Acquisitions

The seeds of galaxy formation were sown in the very early universe, when small density fluctuations in the primordial matter began to grow (see Section 17.7). Our discussion here begins with these "pregalactic" blobs of gas already formed. The masses of these fragments were quite small—only a few million solar masses, comparable to the masses of the smallest present-day dwarf galaxies, which may in fact be remnants of this early time. Most astronomers think that galaxies grew by repeated *merging* of smaller objects, as illustrated in Figure 16.9(a). Contrast this with the process of star formation, in which a large cloud fragments into smaller pieces that eventually become stars. ∞ *(Sec. 11.3)*

Theoretical evidence for this picture of **hierarchical merging** is provided by computer simulations of the early universe, which clearly show merging taking place. Further strong support comes from observations that indicate that galaxies



▲ FIGURE 16.9 **Galaxy Formation** (a) The best current theory of galaxy formation holds that large systems were built up from smaller ones through collisions and mergers, as shown schematically in the drawing at bottom. (b) This photograph, one of the deepest ever taken of the universe, provides "fossil evidence" for hundreds of galaxy shards and fragments, up to 5000 Mpc distant. (c) Enlargements of selected portions of (b) reveal rich (billion-star) "star clusters," all lying within a relatively small volume of space (about 1 Mpc across). Such pregalactic fragments might be about to merge to form a galaxy. The events pictured took place about 10 billion years ago. *(NASA)*



▲ **FIGURE 16.10 Hubble Deep Field** Numerous small, irregularly shaped young galaxies can be seen in this very deep optical image. Known as the Hubble Deep Field-North, this image, made with an exposure of approximately 100 hours, captured objects as faint as 30th magnitude. Redshift measurements (as denoted by the superposed values observed at the Keck Observatory in Hawaii) indicate that some of these galaxies lie billions of megaparsecs from Earth. ∞ *(Sec 15.3)* The field of view is about 2 arc minutes across, or less than 1 percent of the area subtended by the full Moon. *(NASA; Keck)*

at large redshifts (meaning that they are very distant and the light we see was emitted long ago) appear distinctly smaller and more irregular than those found nearby. Figure 16.9(b) (see also Figure 16.10) shows some of these images, which include objects up to 5 billion parsecs away. The vague bluish patches are separate small galaxies, each containing only a few percent of the mass of the Milky Way Galaxy. Their irregular shape is probably the result of galaxy mergers; the bluish coloration comes from young stars that formed during the merging process.

Figure 16.9(c) shows more detailed views of some of the objects in Figure 16.9(b), all lying in the same region of space, about 1 Mpc across and almost 5000 Mpc from Earth. Each blob seems to contain several billion stars spread throughout a distorted spheroid about a kiloparsec across. Their decidedly bluish tint suggests that active star formation is already under way. We see them as they were nearly 10 billion years ago, a group of young galaxies possibly poised to merge into one or more larger objects.

Hierarchical merging provides the conceptual framework for all modern studies of galaxy evolution. It describes a process that began billions of years ago and continues (albeit at a greatly reduced rate) to the present day, as galaxies continue to collide and merge. By studying how galaxy properties vary with distance, and hence look-back time, astronomers try to piece together the merger history of the universe. ∞ ***(More Precisely 15-1)***

Figure 16.10 is a remarkable *Hubble* image showing billions of years of galaxy evolution in a single tiny patch of the sky. The large, bright galaxies with easily discernible Hubble types are mostly (according to their redshifts) relatively nearby objects. They are seen here against a backdrop of small, faint, irregular galaxies lying much farther away. The size and appearance of these distant galaxies compared with those in the foreground strongly support the basic idea that galaxies grew by mergers and were smaller and less regular in the past.

Evolution and Interaction

Left alone, a galaxy will evolve slowly and fairly steadily as interstellar clouds of gas and dust are turned into new generations of stars and main sequence stars evolve into giants and ultimately into compact remnants—white dwarfs, neutron stars, and black holes. ∞ *(Secs. 11.3, 13.5)* The galaxy's overall color, composition, and appearance change in a more or less predictable way as the cycle of stellar evolution recycles and enriches the galaxy's interstellar matter. ∞ *(Sec. 12.7)*

If the galaxy is an elliptical, lacking interstellar gas, it will tend to become fainter and redder in time as its more massive stars burn out and are not replaced. ∞ *(Sec. 12.6)* For a gas-rich galaxy, such as a spiral or irregular, hot, bright stars will lend a bluish coloration to the overall light for as long as gas remains available to form them. As in our own Galaxy, the star-forming lifetime of a spiral disk may be prolonged by infall of fresh gas from the galaxy's surroundings. ∞ *(Sec. 14.4)*

But many galaxies—perhaps most—are not alone. They reside in small groups and clusters, and as we have just seen, their orderly "internal" evolution can be significantly complicated by external events—close encounters, mergers, and the accumulation of smaller satellite galaxies over extended periods of time. As described in Section 16.2, these interactions can rearrange a galaxy's internal structure and trigger sudden, intense bursts of star formation. Encounters may also divert fuel to a central black hole, powering violent activity in some galactic nuclei. ∞ *(Sec. 15.5)* Thus, starbursts and nuclear activity are key indicators of interactions and mergers between galaxies.

Careful studies of starburst galaxies and active galactic nuclei indicate that most such encounters probably took place long ago—in galaxies having redshifts greater than about 1, meaning that we see them as they were roughly 10 billion years ago (see Table 15.2). The galaxy interactions observed in the local universe are the extension of this same basic process into the present day. Figure 16.11 presents a graphical summary of these (mostly) ancient events.

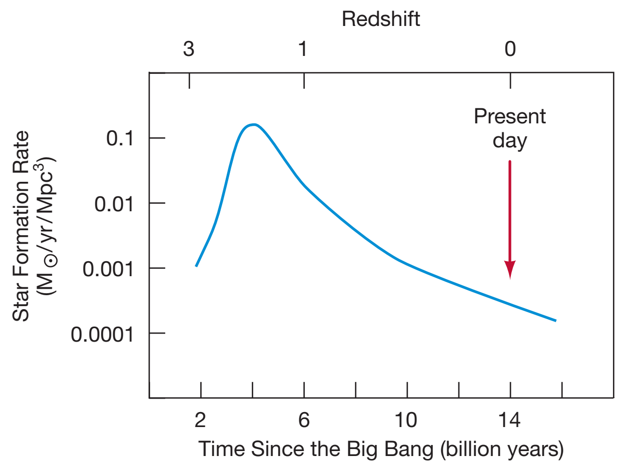
The many different types and masses of galaxies lead to an almost bewildering variety of possible interactions. Here we highlight just a few. Consider first two galaxies orbiting one another—a binary galaxy system. As they orbit, the galaxies interact with each other's dark halos, one galaxy stripping halo material from the other by tidal forces. The freed matter is redistributed between the galaxies or is entirely lost from the binary system. In either case, the interaction changes the orbits of the galaxies, causing them to spiral toward one another and eventually to merge.

If one galaxy of the pair happens to have a much lower mass than the other, the process is colloquially termed *galactic cannibalism*. Such cannibalism might explain why supermassive galaxies are often found at the cores of rich galaxy clusters. Having dined on their companions, they now lie at the center of the cluster, waiting for more food to arrive. Figure 16.12 is a remarkable combination of images that has apparently captured this process at work.

We can also find examples of galactic cannibalism closer to home. Figure 16.13(a) illustrates how the disruption of a dwarf galaxy by the Milky Way leaves behind a **tidal stream** of stripped stars, all with similar orbits and composition, still following the orbital path of their parent galaxy. The small Sagittarius dwarf galaxy (see Figure 15.12) is well on its way to suffering such a fate, and theory suggests that the Magellanic Clouds (Figure 15.7) will eventually meet the same end. ∞ *(Sec. 15.2)* Astronomers have discovered numerous tidal streams in the halo of the Milky Way. ∞ *(Sec. 14.4)* Figure 16.13(b) is a wide-angle Sloan Digital Sky Survey mosaic (see Discovery 16-1) of roughly half of the northern sky, looking in the direction away from the Galactic center. It shows several streams of stars crossing the field of view. The most prominent streams (marked) represent two orbits of the Sagittarius dwarf over the past 500 million years. Their locations in the sky are consistent with the measured orbital properties of the Sagittarius galaxy, which currently lies in the opposite direction, as seen from Earth.

Now consider two interacting disk galaxies, one a little smaller than the other but each having a mass comparable to the Milky Way Galaxy. As shown in the computer-generated frames of Figure 16.14, the smaller galaxy can substantially distort the larger one, causing spiral arms to appear where none existed before. The entire event requires several hundred million years—a span of evolution that a supercomputer can model in minutes. The final frame of Figure 16.14 looks remarkably similar to the double galaxy shown in Figure 15.2(b), demonstrating how the two galaxies might have interacted millions of years ago and how spiral arms might have been created or enhanced as a result.

What if the colliding galaxies are comparable in size and mass? Computer simulations reveal that such a merger can destroy a spiral galaxy's disk, creating a galaxywide starburst episode. ∞ *(Sec. 15.4)* The violence of the merger and the

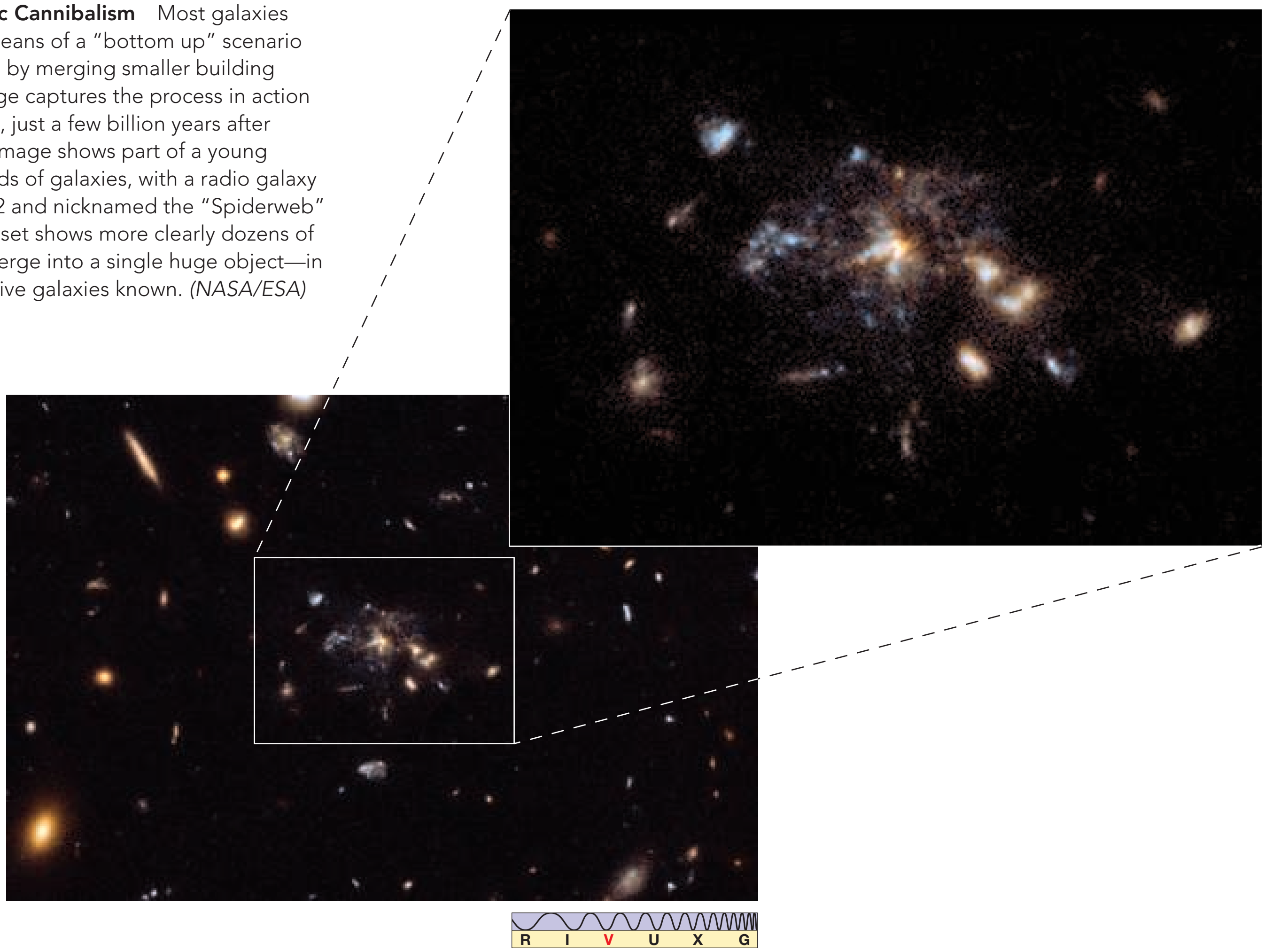


▲ **FIGURE 16.11 Galaxies Build and Stars Form** Observations of the luminosities of many different galaxies at various distances from us show that the star formation rate in the universe peaked a few billion years after the Big Bang. That epoch marked the time at which galaxies were growing most rapidly, as smaller galaxies merged to form the largest systems.

MA INTERACTIVE
Starburst Galaxy M82

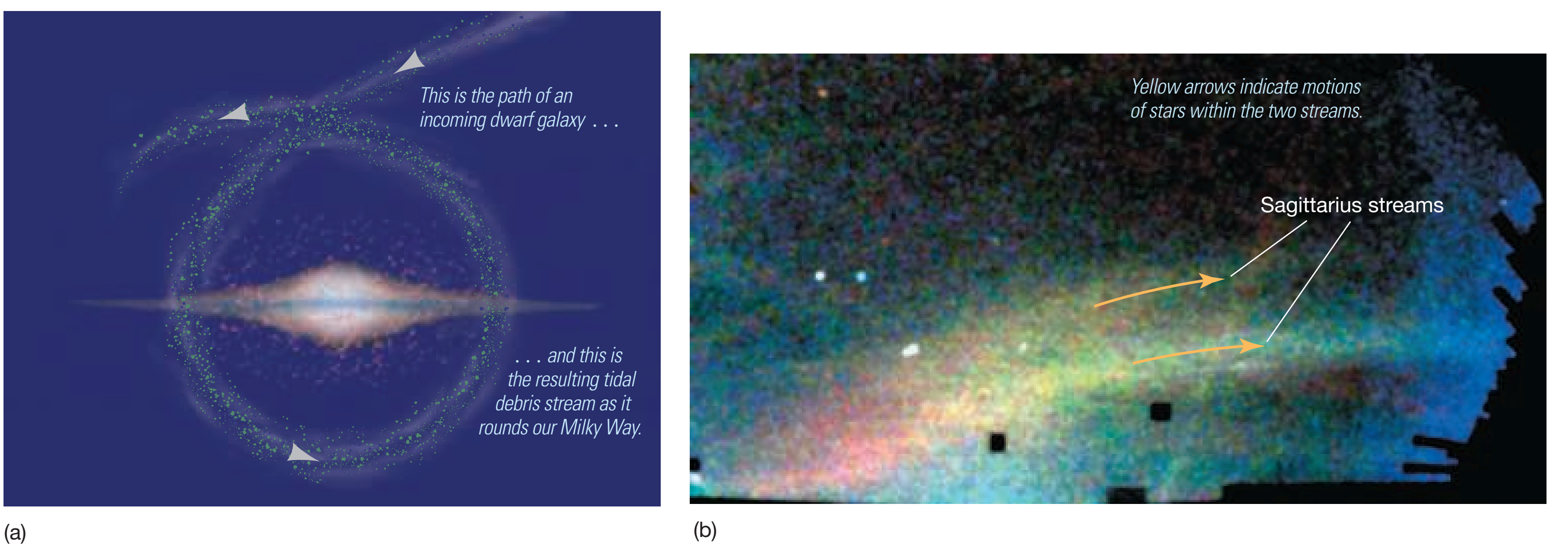
MA ANIMATION/VIDEO
Hubble Deep Field Zoom I

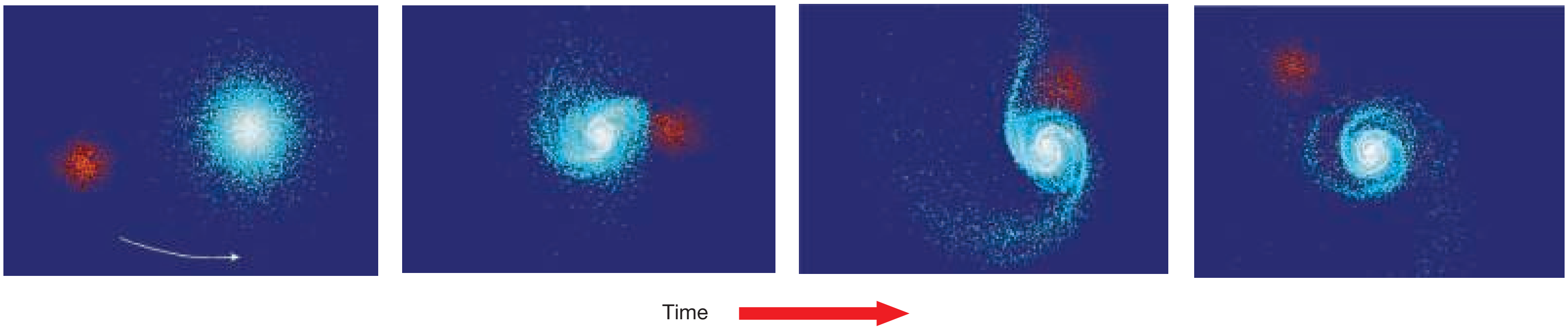
MA ANIMATION/VIDEO
Hubble Deep Field Zoom II



▶ **FIGURE 16.12 Galactic Cannibalism** Most galaxies probably developed by means of a "bottom up" scenario that formed large systems by merging smaller building blocks. This dramatic image captures the process in action about 10 billion years ago, just a few billion years after the Big Bang. The larger image shows part of a young cluster containing hundreds of galaxies, with a radio galaxy catalogued MRC 1138-262 and nicknamed the "Spiderweb" galaxy at its center. The inset shows more clearly dozens of small galaxies about to merge into a single huge object—in fact one of the most massive galaxies known. *(NASA/ESA)*

▼ **FIGURE 16.13 Tidal Streams in the Milky Way** (a) Breakup and dispersal of the contents of an incoming galaxy companion captured by our Milky Way. Eventually, the smaller galaxy dissolves, much as other dwarf companion galaxies were probably consumed by our Galaxy long ago. (b) This view of the outer part of the Milky Way shows innumerable stars that have been torn from disrupted satellite galaxies (colors indicate distance, with blue being closest). Several tidal streams are evident, the biggest one at center showing two orbits of the enormous, arching death spiral of the Sagittarius dwarf galaxy. *(V. Belokurov; SDSS)*





▲ **FIGURE 16.14 Galaxy Interaction** Galaxies can change their shapes long after their formation. In this computer-generated sequence, two galaxies closely interact over several hundred million years. The smaller galaxy, in red, has gravitationally disrupted the larger galaxy, in blue, changing it into a spiral galaxy. Compare the result of this supercomputer simulation with Figure 15.2(b), a photograph of M51 and its small companion. *(J. Barnes & L. Hernquist)*

effects of subsequent supernovae eject much of the remaining gas into intergalactic space, creating the hot intracluster gas noted in Section 16.1. Once the burst of star formation has subsided, the resulting object looks very much like an elliptical galaxy. The elliptical's hot X-ray halo is the last vestige of the original spiral's disk. ∞ *(Sec. 15.1)* The merging galaxies in Figure 16.8 and the irregular galaxies in Figure 16.7 may be examples of this phenomenon in progress. The blue blobs in some of these images are young star clusters formed during the starburst, and the explosive appearance of especially Figure 16.7(c) suggests that we are witnessing gas and dust being ejected.

CONCEPT CHECK

Why would we expect the evolution of galaxies in voids to differ from that of galaxies in clusters?

Making the Hubble Sequence

If galaxies form and evolve by repeated mergers, can we account for the Hubble sequence and, specifically, differences between spirals and ellipticals? ∞ *(Sec. 15.1)* The details are still far from certain, but remarkably, the answer now seems to be a qualified yes. Collisions and close encounters are random events and do not represent a genuine evolutionary sequence linking all galaxies. However, computer simulations suggest a plausible way in which the observed Hubble types might have arisen, starting from a universe populated only by irregular, gas-rich galaxy fragments.

As we have just seen, the simulations reveal that "major" mergers—collisions between large galaxies of comparable size—tend to destroy galactic disks, effectively turning spirals into ellipticals. On the other hand, "minor" mergers, in which a small galaxy interacts with, and ultimately is absorbed by, a larger one, generally leave the larger galaxy intact, with more or less the same Hubble type as it had before the merger. This is the most likely way for large spirals to grow—in particular, our own Galaxy probably formed in such a manner.

Supporting evidence for this general picture comes from observations that spiral galaxies are relatively rare in regions of high galaxy density, such as the central regions of rich galaxy clusters. This is consistent with the view that their fragile disks are easily destroyed by collisions, which are more common in dense galactic environments. Spirals also seem to be more common at larger redshifts (that is, in the past), implying that their numbers are decreasing with time, presumably also as the result of collisions. However, nothing in this area of astronomy is clear-cut. Astronomers know of numerous isolated elliptical galaxies in low-density regions of the universe that are hard to explain as the result of mergers.

In principle, the starbursts associated with galaxy mergers leave their imprint on the star-formation history of the universe in a way that can be correlated with the properties of galaxies. As a result, studies of star formation in distant galaxies have become a very important way of testing and quantifying the details of the entire hierarchical merger scenario.

PROCESS OF SCIENCE CHECK

In what ways can astronomers test the predictions of the hierarchical merger scenario?

16.4 Black Holes in Galaxies

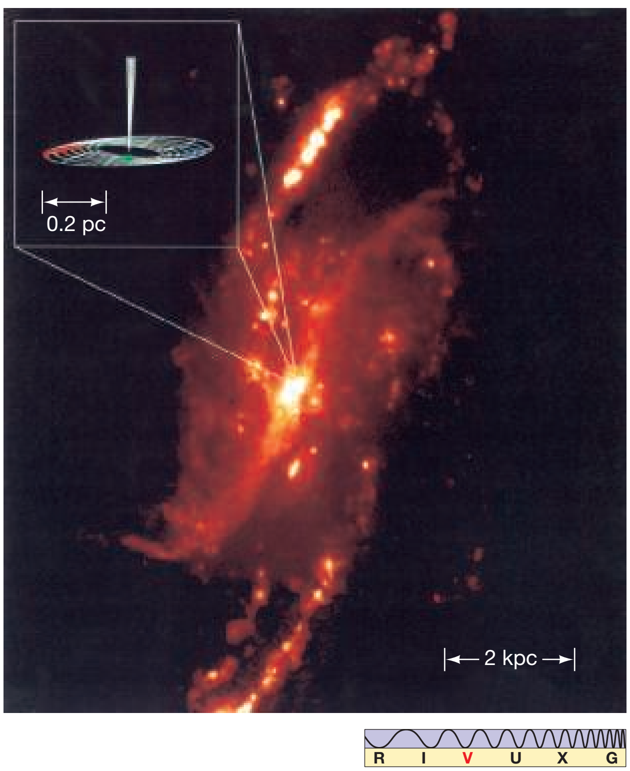
ANIMATION/VIDEO
Galaxy Collision II

Now let's ask how quasars and active galaxies fit into the framework of galaxy evolution just described. The fact that quasars are more common at great distances from us demonstrates that they were much more prevalent in the past than they are today. ∞ (Sec. 15.4) Quasars have been observed with redshifts exceeding 7, and some observers have reported galaxy redshifts of more than 10, so the process must have started at least 13 billion years ago (see Table 15.2). However, most quasars have redshifts between 2 and 3, corresponding to an epoch some 2 billion years later. Most astronomers agree that quasars represent an early stage of galaxy evolution—an "adolescent" phase of development, prone to frequent flare-ups and outbursts before settling into more steady "adulthood." This view is reinforced by the fact that the same black hole energy-generation mechanism can account for the luminosities of quasars, active galaxies, and the central regions of normal galaxies like our own.

Black Hole Masses

In Chapter 15 we saw the standard model of active galactic nuclei accepted by most astronomers—accretion of gas onto a supermassive black hole. ∞ (Sec. 15.5) We also saw that a large fraction of all "bright" galaxies exhibit activity of some sort, even though in many cases it represents only a small fraction of the galaxy's total energy output. This suggests that these galaxies may also harbor central black holes with the potential of far greater activity under the right circumstances. Our own Galaxy is a case in point. ∞ (Sec. 14.7) The 3- to 4-million-solar-mass black hole at the center of the Milky Way is not currently active, but if fresh fuel were supplied (say, by a star or molecular cloud coming too close to the hole's intense gravitational field), it might well become a (relatively weak) active galactic nucleus.

In recent years, astronomers have found that many bright normal galaxies have supermassive black holes at their centers. Figure 16.15 presents perhaps the most compelling evidence for a supermassive black hole at the center of a normal galaxy. Using the Very Long Baseline Array, a continent-wide interferometer comprising 10 radio telescopes, a U.S.–Japanese team has achieved an angular resolution hundreds of times better than that attainable with the *Hubble* telescope. ∞ (Sec. 3.4) The observations reveal a group of molecular clouds swirling in an organized fashion about the galaxy's center. Doppler measurements indicate a slightly warped, spinning disk centered precisely on the galaxy's heart. The rotation speeds imply the presence of more than 40 million solar masses packed into a region less than 0.2 pc across.



▲ **FIGURE 16.15 Galactic Black Hole** A network of radio telescopes has probed the core of the spiral galaxy NGC 4258, shown here in the light of mostly hydrogen emission. Within the innermost region (inset) a disk of Doppler-shifted molecular clouds (designated by red, green, and blue dots) obey Kepler's third law perfectly, apparently revealing a huge black hole at the center of the disk. *(J. Moran)*

Similar evidence exists for supermassive black holes in the nuclei of several dozen bright galaxies—some normal, some active—within a few tens of megaparsecs of the Milky Way. Some observers would go so far as to say that in every case where a galaxy has been surveyed and a black hole *could* have been detected, given the resolution and the sensitivity of the observations, a black hole *has* in fact been found. It is a small step to the remarkable conclusion that *every bright galaxy—active or not—contains a central supermassive black hole.* This unifying principle connects our theories of normal and active galaxies in a fundamental way.

Astronomers have also found a correlation between the masses of the central black holes and the properties of the galaxy in which they reside. As illustrated in Figure 16.16, the largest black holes tend to be found in the most massive galaxies (as measured by the mass of the bulge). The reason for this correlation is not fully understood, but most astronomers take it to mean that the evolution of normal and active galaxies must be very closely connected, as we now discuss.

The Quasar Epoch

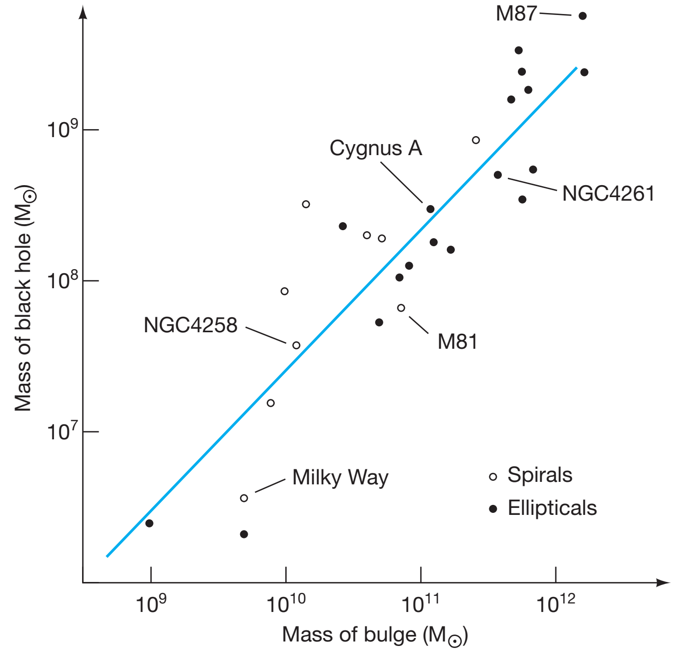
Where did the supermassive black holes in galaxies come from? To be honest, the processes whereby the first billion-solar-mass black holes formed early in the history of the universe are not fully understood. The accretion rates needed to form the oldest known massive systems challenge current theoretical models. However, the accretion responsible for the energy emission also naturally accounts for the mass of the black hole—only a few percent of the infalling mass is converted to energy; the rest is trapped forever in the black hole once it crosses the event horizon. ∞ *(Sec. 13.5)*. Simple estimates suggest that the accretion rates needed to power the quasars are generally consistent with black-hole masses inferred by other means.

Since the brightest known quasars devour about a thousand solar masses of material every year, it is unlikely that they could maintain their luminosity for very long—even a million years would require a billion solar masses, enough to account for the most massive black holes known. ∞ *(Sec. 15.4)* This suggests that a typical quasar spends only a fairly short amount of time in its highly luminous phase—perhaps a few million years—before running out of fuel. Thus, most quasars were relatively brief events that occurred long ago.

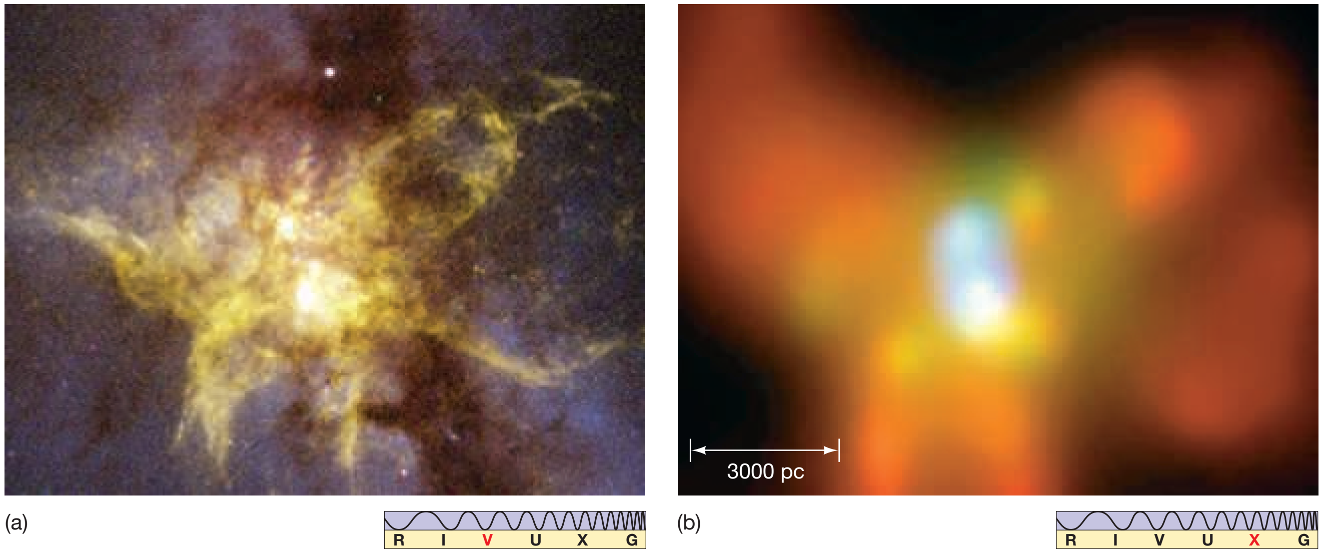
To make a quasar, we need a black hole and enough fuel to power it. While fuel was abundant at early times in the universe's history in the form of gas and newly formed stars, black holes were not. They had yet to form, most probably by the same basic stellar evolutionary processes we saw in Chapter 12, although the details are still not known. ∞ *(Sec. 12.4)* The building blocks of the supermassive black holes that would ultimately power the quasars may well have been relatively small black holes having masses tens or perhaps a few hundreds of times the mass of the Sun. These small black holes sank to the center of their still-forming parent galaxy and merged to form a single, more massive black hole.

As galaxies merged, so, too, did their central black holes, and eventually supermassive (1-million- to 1-billion-solar mass) black holes existed in the centers of many young galaxies. Some supermassive black holes may have formed directly by the gravitational collapse of the dense central regions of a protogalactic fragment or perhaps by accretion or a rapid series of mergers in a particularly dense region of the universe. These events resulted in the earliest (redshift 6–7) quasars known, shining brightly 13 billion years ago. However, in most cases, the mergers took longer—roughly another 2 billion years. By then (at redshifts between 2 and 3, roughly 11 billion years ago), many supermassive black holes had formed, and there was still plenty of merger-driven fuel available to power them. This was the height of the "quasar epoch" in the universe.

Until recently, astronomers were confident that black holes would merge when their parent galaxies collided, but they had no direct evidence of the process—no image of two black holes "caught in the act." In 2002, the *Chandra* X-ray observatory discovered a binary black hole—two supermassive objects, each having a mass a few tens of millions of times that of the Sun—in the center of the ultraluminous starburst galaxy NGC 6240, itself the product of a galaxy merger some 30 million years ago. Figure 16.17 shows optical and X-ray views of the system. The black holes are the two blue-white objects near the center of the (false-color) X-ray image. Orbiting just 1000 pc apart, they are losing energy through interactions with stars and gas and are predicted to merge in about 400 million years. Astronomers now know of several binary black holes in relatively nearby galaxies, caught in the act of spiraling together on their way to merging. NGC 6240 lies just 120 Mpc from Earth, so we are far from seeing a quasar merger in the early universe. Nevertheless, astronomers think that events similar to this must have occurred countless times billions of years ago, as galaxies collided and quasars blazed.



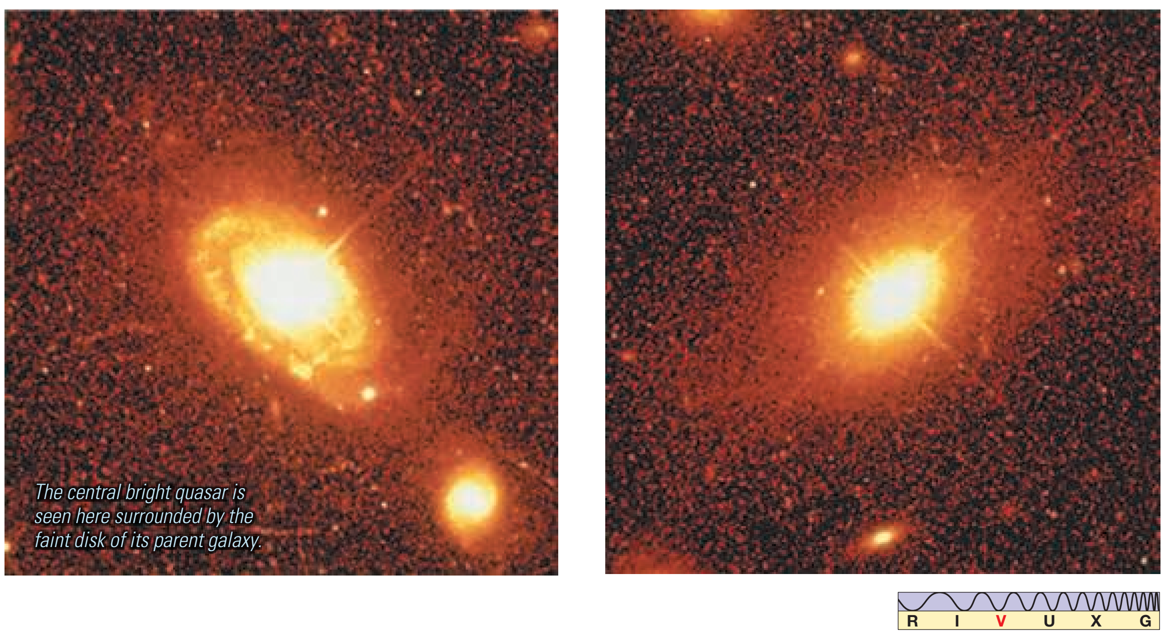
▲ **FIGURE 16.16 Black Hole Masses** Observations of nearby normal and active galaxies show that the mass of the central black hole is closely correlated with the mass of the galactic bulge. The straight line is the best fit to the data points for many galaxies, implying a black hole mass of $^1/_{200}$ the mass of the bulge. *(L. Ferrarese)*



▶ **FIGURE 16.17 Binary Black Hole** These (a) optical (*Hubble*) and (b) X-ray (*Chandra*) images of the starburst galaxy NGC 6420 show two supermassive black holes (the blue-white objects near the center of the X-ray image) orbiting about 1 kpc apart. Theoretical estimates imply that they will merge in about 400 million years, releasing an intense burst of gravitational radiation. ∞ *(Discovery 13-1)* *(NASA)*

Distant galaxies are generally much fainter than their bright quasar cores. As a result, until quite recently, astronomers were hard-pressed to discern any galactic structure in quasar images. Since the mid-1990s, several groups of astronomers have used the *Hubble Space Telescope* to search for the "host" galaxies of moderately distant quasars. After removing the bright quasar core from the *HST* images and carefully analyzing the remnant light, the researchers have reported that in every case studied—several dozen quasars so far—a host galaxy can be seen enveloping the quasar. Figure 16.18 shows some of the longest quasar exposures ever taken. Even without sophisticated computer processing, the hosts are clearly visible.

As we saw in Chapter 15, the connection between active galaxies and galaxy clusters is well established, and many relatively nearby quasars are also known to be members of clusters. ∞ ***(Sec. 15.4)*** The link is less clear-cut for the most distant quasars, however, simply because they are so far away that other cluster members are very faint and extremely hard to see. However, as the number of known quasars continues to increase, evidence for quasar clustering



▶ **FIGURE 16.18 Quasar Host Galaxies** These long-exposure images of distant quasars show the young host galaxies in which the quasars reside, lending support to the idea that quasars represent an early, very luminous phase of galactic evolution. The quasar at the left is the best example, having the catalog name PG0052 + 251 and residing roughly 690 Mpc from Earth. *(NASA)* (and presumably, therefore, for quasar membership in young galaxy clusters) mounts. Thus, as best we can tell, quasar activity—and, in fact, galaxy activity of *all* sorts—is intimately related to interactions and collisions in galaxy clusters.

This connection also suggests a possible way in which the growth of black holes might be tied to the growth of their parent galaxies. Astronomers speculate that a process called **quasar feedback**, in which some fraction of the quasar's enormous energy output is absorbed by the surrounding galactic gas, might help explain the correlation of black hole and bulge masses shown in Figure 16.16. According to this view, which is appealing but by no means certain, the absorbed energy expels the gas from the galaxy, simultaneously shutting down both galactic star formation and the quasar's own fuel supply, thus tying the growth of the central black hole to the formation of new stars in the bulge.

Active and Normal Galaxies

Early on, frequent mergers may have replenished the quasar's fuel supply, extending its luminous lifetime. However, as the merger rate declined, these systems spent less and less of their time in the "bright" phase. The rapid decline in the number of bright quasars roughly 10 billion years ago marks the end of the quasar epoch. Today, the number of quasars has dropped virtually to zero (recall that the nearest lies hundreds of megaparsecs away). ∞ *(Sec. 15.4)*

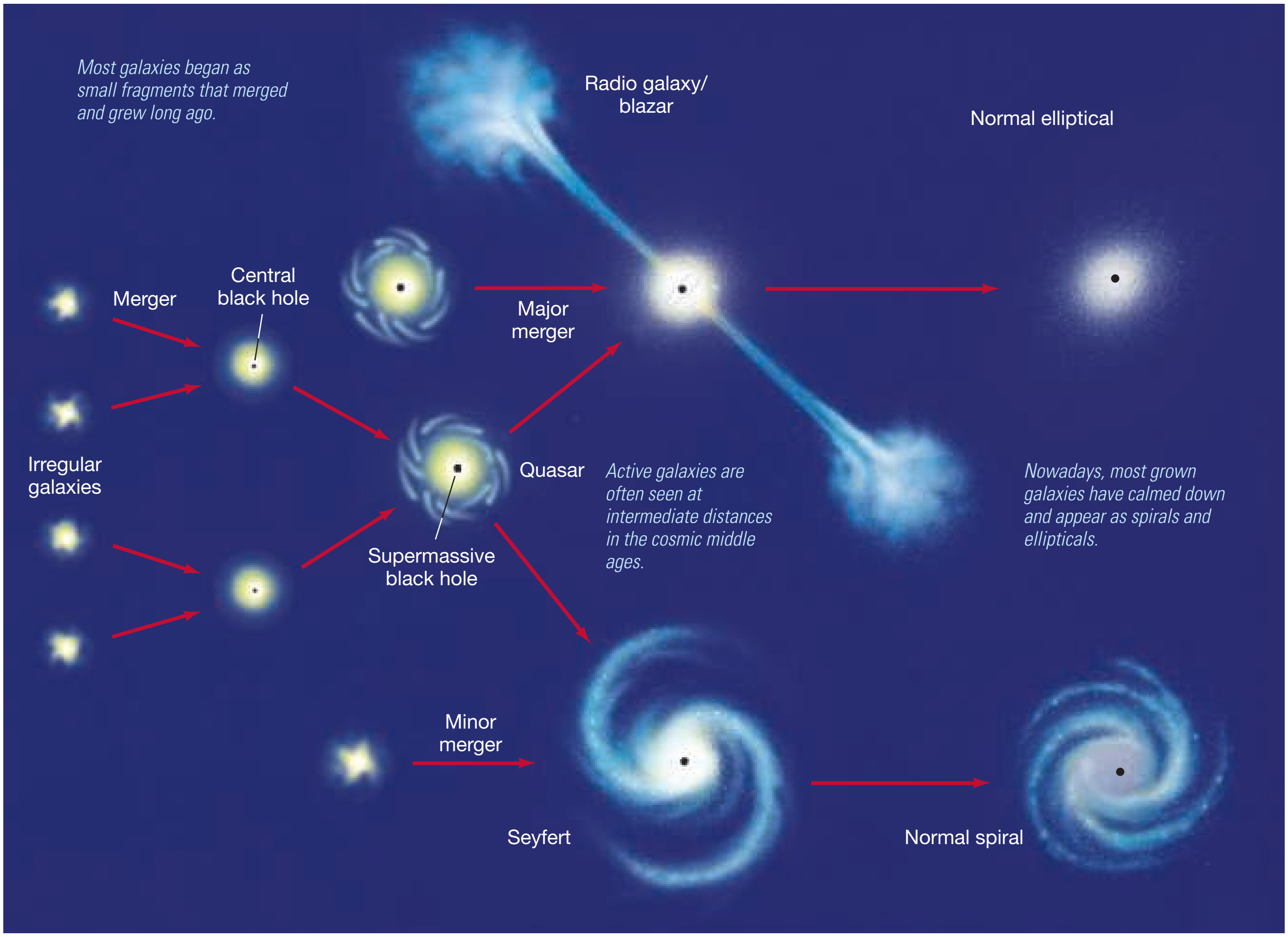
Large black holes do not simply vanish. If a galaxy contained a bright quasar 10 billion years ago, the black hole responsible for all that youthful activity must still be present in the center of the galaxy today. We see some of these black holes as active galaxies. The remainder reside dormant in normal galaxies all around us. In this view, *the difference between an active galaxy and a normal one is mainly a matter of fuel supply*. When the fuel runs out and a quasar shuts down, its central black hole remains behind, its energy output reduced to a relative trickle. The black holes at the hearts of normal galaxies are quiescent, awaiting another interaction to trigger a new active outburst. Occasionally, two nearby galaxies may interact, causing a flood of new fuel to be directed toward the central black hole of one or both. The engine starts up for a while, giving rise to the nearby active galaxies—Seyferts, radio galaxies, and others—we observe.

Should this general picture be correct, it follows that many relatively nearby galaxies (but probably *not* our own Milky Way, whose central black hole is even now only a paltry 3–4 million solar masses) must once have been brilliant quasars. ∞ *(Sec. 14.7)* Perhaps some alien astronomer, thousands of megaparsecs away, is at this very moment observing the progenitor of M87 in the Virgo Cluster—seeing it as it was billions of years ago—and is commenting on its enormous luminosity, nonstellar spectrum, and high-speed jets and wondering what exotic physical process can possibly account for its violent activity! ∞ *(Sec. 14.4)*

Finally, Figure 16.19 suggests some possible (but unproven) evolutionary connections among quasars, active galaxies, and normal galaxies. If the largest black holes reside in the most massive galaxies, and also tend to power the brightest active galactic nuclei, then we would expect that the most luminous nuclei should reside in the largest galaxies, which probably came into being via "major" mergers of other large galaxies. Since the products of such mergers are elliptical galaxies, we have a plausible explanation of why the brightest active galaxies—the radio galaxies—should be associated with large ellipticals. ∞ *(Sec. 15.4)* The path to spiral galaxies would have entailed a series of mergers involving smaller galaxies, resulting in the less violent Seyferts along the way.

PROCESS OF SCIENCE CHECK

How does the existence of supermassive black holes in normal galaxies fit in with theories of active galaxy evolution?



▲ **FIGURE 16.19 Galaxy Evolution** Most evolutionary sequences for galaxies began with galaxy mergers that led to highly luminous quasars, after which they decreased in violence through the radio and Seyfert galaxies, eventually resulting in normal ellipticals and spirals. The central black holes that powered the early activity remain at later times, but many of them have run out of fuel.

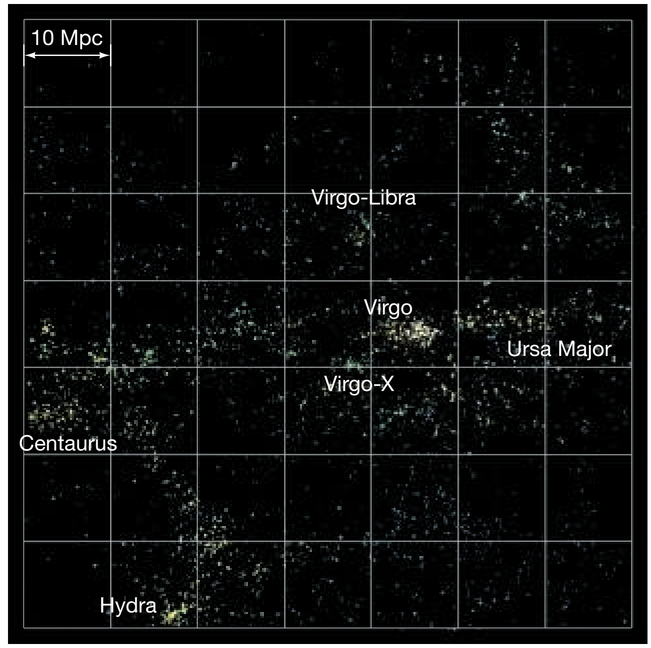
Active Galaxies and the Scientific Method

When active galactic nuclei—and especially quasars—were first discovered, their extreme properties defied conventional explanation. Initially, the idea of supermassive (million- to billion-solar mass) black holes in galaxies was just one of several competing, and very different, hypotheses advanced to account for the enormous luminosities and small sizes of those baffling objects. Some astronomers suggested instead that the energy source might be multiple supernova explosions, others that perhaps some exotic form of matter–antimatter annihilation was taking place. A few went so far as to propose that these inexplicable objects demanded an even more radical explanation: that Hubble's law was incorrect and that the large redshifts of quasars had some other, unknown cause.

However, as observational evidence mounted, the other hypotheses were abandoned one by one, and massive black holes in galactic nuclei became first the leading, and eventually the standard, theory of active galaxies. As often happens in science, a theory once itself considered extreme is now the accepted explanation. Far from threatening the laws of physics, as some astronomers once feared, active galaxies are now an integral part of our understanding of how galaxies form and evolve. The synthesis of studies of normal and active galaxies, galaxy formation, and large-scale structure is one of the great triumphs of extragalactic astronomy.

CONCEPT CHECK

Does *every* galaxy have the potential for activity?



▶ **FIGURE 16.20 Local Supercluster** More than 4500 galaxies are plotted here in the vicinity of the Virgo cluster, and several prominent galaxy clusters are labeled. The diagram depicts the Virgo Supercluster roughly as we see it from our own Galaxy, which is located approximately 20 Mpc (two grid squares) above the page. Notice the supercluster's irregular, elongated shape. *(B. Tully and S. Levy)*

16.5 The Universe on Very Large Scales

Many galaxies, including our own, are members of galaxy clusters—megaparsec-sized structures held together by their own gravity. ∞ *(Sec. 15.2)* Our own small cluster is called the Local Group. Figure 16.20 shows the locations of the Virgo Cluster, the closest "large" cluster, and of several other well-defined clusters in our cosmic neighborhood. The region displayed is about 70 Mpc across. Each point in the figure represents an entire galaxy whose distance has been determined by one of the methods described in Chapter 15.

Clusters of Clusters

Do galaxy clusters top the cosmic hierarchy, or does the universe have even larger groupings of matter? Most astronomers have concluded that the galaxy clusters are themselves clustered, forming titanic agglomerations of matter known as **superclusters**.

Together, the galaxies and clusters shown in Figure 16.20 form the *Local Supercluster*, also known as the Virgo Supercluster. Aside from the Virgo Cluster itself, it contains the Local Group and numerous other clusters lying within about 20–30 Mpc of Virgo. Most of the galaxies depicted in the figure are fairly large spirals and ellipticals; the fainter irregulars and dwarfs are not included in the diagram. Figure 16.21 shows a three-dimensional rendering of an even wider view, illustrating the Virgo Supercluster (near the center) relative to other "nearby" galaxy superclusters within a vast imaginary rectangle roughly 100 Mpc on its short side.

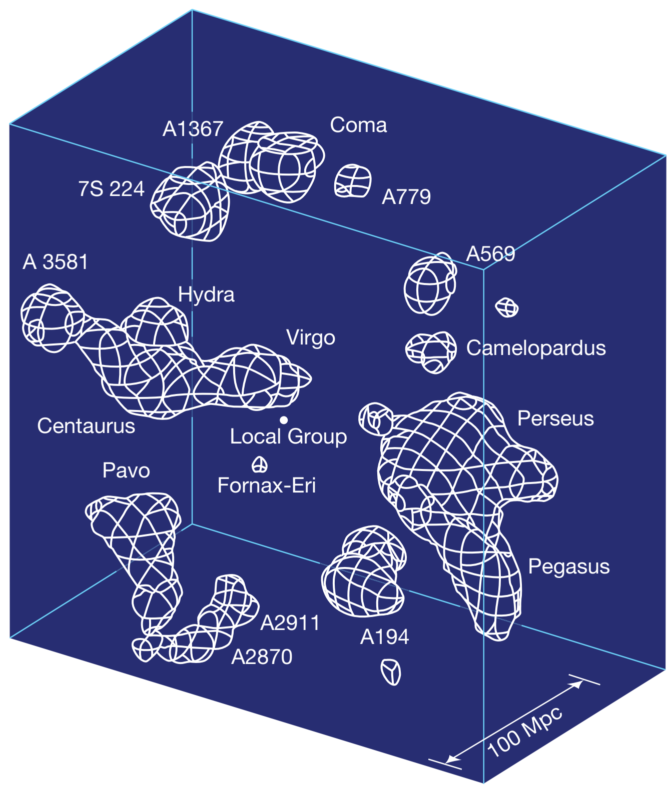
All told, the Local Supercluster is about 40–50 Mpc across, contains some 10^{15} solar masses of material (several tens of thousands of galaxies), and is very irregular in shape. The Local Supercluster is significantly elongated perpendicular to the line joining the Milky Way to Virgo, with its center lying near the Virgo Cluster. By now it should come as no surprise that the Local Group is *not* found at the heart of the Local Supercluster—we live far off in the periphery, about 18 Mpc from the center.

Redshift Surveys

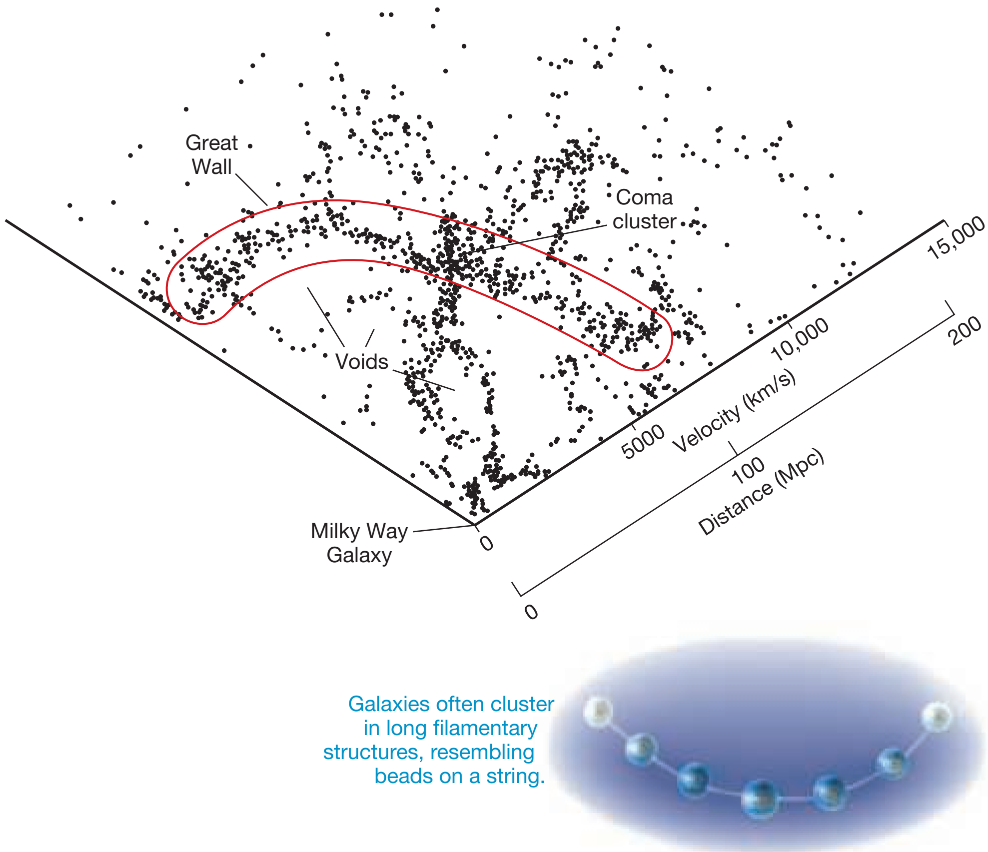
The farther we peer into deep space, the more galaxies, clusters of galaxies, and superclusters we see. Is there structure on even larger scales? To answer this question, astronomers use Hubble's law to map out the distribution of galaxies in the universe and have developed indirect techniques to probe the dark recesses of intergalactic space.

Figure 16.22 shows part of an early survey of the universe performed by astronomers at Harvard University in the 1980s. Using Hubble's law as a distance indicator, the team systematically mapped out the locations of galaxies within about 200 Mpc of the Milky Way in a series of wedge-shaped "slices," each 6° thick, starting in the northern sky. The first slice (Figure 16.22) covered a region of the sky, which happens to lie in a direction almost perpendicular to our Galaxy's plane. Because redshift is used as the primary distance indicator, these studies are known as *redshift surveys*.

MA® ANIMATION/VIDEO
Cluster Merger



▲ **FIGURE 16.21 Virgo Supercluster in 3-D** The elongated shape of the Virgo Supercluster (left) is mapped relative to other neighboring galaxy superclusters within about 100 Mpc of the Milky Way (within the Local Group near center). Individual galaxies are not shown; rather, smoothed contour plots outline galaxy clusters, each named or numbered by its most prominent member. *(M. Hudson)*



▲ **FIGURE 16.22 Galaxy Survey** A "slice" of the universe, covering 1732 galaxies out to a distance of about 200 Mpc, shows that galaxies and clusters are not randomly distributed on large scales. Instead, they appear to have a filamentary structure, surrounding vast, nearly empty voids. The large Coma cluster of galaxies near the center of the slice can also be seen in Figure 16.21. *(Harvard-Smithsonian Center for Astrophysics)*

The most striking feature of maps such as this is that the distribution of galaxies on very large scales is decidedly nonrandom. The galaxies appear to be arranged in a network of strings, or filaments, surrounding large, relatively empty regions of space known as **voids**. Voids account for some 50 percent of the total volume of the nearby universe, but only 5–10 percent of the mass. The biggest voids measure some 100 Mpc across. The most likely explanation for the voids and filamentary structure in Figure 16.22 is that the galaxies and galaxy clusters are spread across the surfaces of vast "bubbles" in space. The voids are the interiors of these gigantic bubbles. The galaxies seem to be distributed like beads on strings only because of the way our slice of the universe cuts through the bubbles. Like suds on soapy water, these bubbles fill the entire universe. The densest clusters and superclusters lie in regions where several bubbles meet. The elongated shape of the Virgo Supercluster (see Figure 16.20) is a local example of this same filamentary structure.

Most theorists think that this "frothy" distribution of galaxies, and in fact all structure on scales larger than a few megaparsecs, traces its origin directly to conditions in the very earliest stages of the universe (Chapter 17). As such, studies of large-scale structure are vital to our efforts to understand the origin and nature of the cosmos itself. The idea that the filaments are the intersection of the survey slice with much larger structures (the bubble surfaces) was confirmed when the next three slices of the survey, lying above and below the first, were completed. The region of Figure 16.22 indicated by the red outline was found to continue through both the other slices. This extended sheet of galaxies, which has come to be known as the *Great Wall*, measures at least 70 Mpc (out of the plane of the page) by 200 Mpc (across the page). It is one of the largest known structures in the universe.

Figure 16.23 shows a more recent redshift survey, considerably larger than the one presented in Figure 16.22. This survey includes nearly 24,000 galaxies within about 750 Mpc of the Milky Way. Numerous voids and "Great Wall-like" filaments can be seen (some are marked), but apart from the general fall-off in numbers of galaxies at large distances—basically because the more distant galaxies are harder to see due to the inverse-square law—there is no obvious evidence for any structures on scales larger than about 200 Mpc. Careful statistical analysis and even larger surveys (see *Discovery* 16-*1*) confirm this impression. Apparently, voids and walls represent the largest structures in the universe. We will return to the far-reaching implications of this fact in Chapter 17.

Quasar Absorption Lines

CONCEPT CHECK

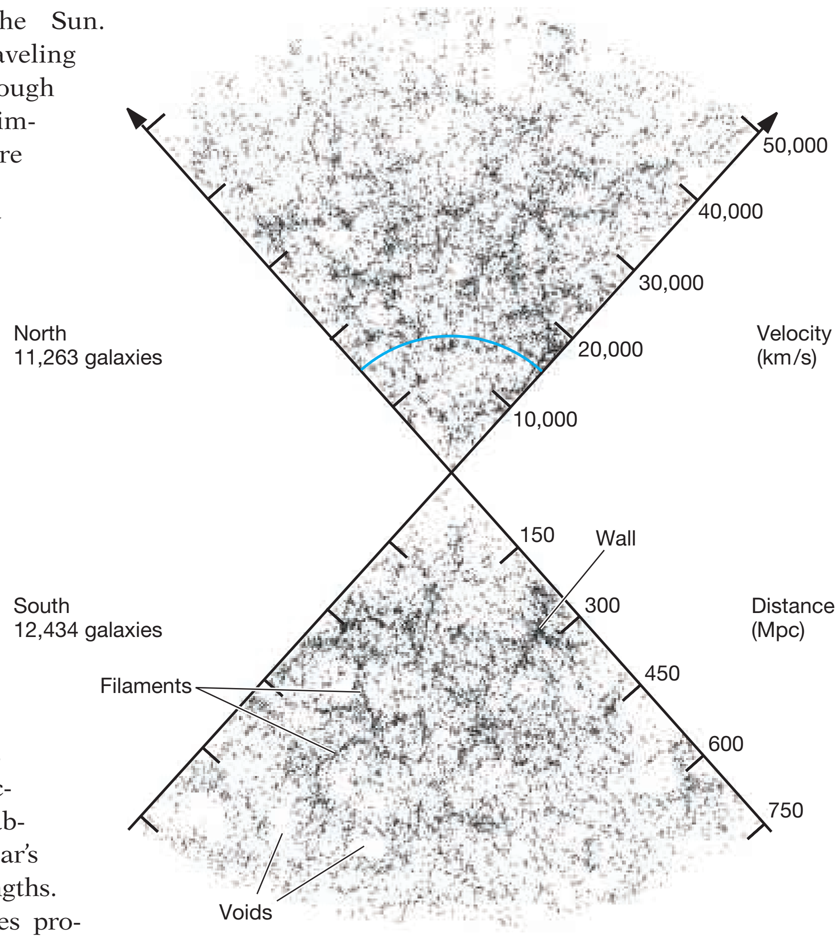
What do observations of distant quasars tell us about the structure of the universe closer to home?

How can we probe the structure of the universe on very large scales? As we have seen, much of the matter is dark, and even the "luminous" component is so faint that it is hard to detect at large distances. One way to study large-scale structure is to take advantage of the great distances, point-like appearance, and large luminosities of quasars, in much the same way as astronomers use bright stars to probe the interstellar medium near the Sun. *(Secs. 11.1, 15.3)* Since quasars are so far away, light traveling from a quasar to Earth has a pretty good chance of passing through or near something "interesting" en route. By analyzing quasar images and spectra, it is possible to piece together a partial picture of the intervening space.

In addition to their own strongly redshifted spectra, many quasars also show additional absorption features that are redshifted by substantially *less* than the lines from the quasar itself. For example, the quasar PHL 938 has an emission-line redshift of 1.954, placing it at a distance of some 5200 Mpc, but it also shows absorption lines having redshifts of just 0.613. These are interpreted as arising from intervening gas that is much closer to us (only about 2200 Mpc away) than the quasar itself. Most probably this gas is part of an otherwise invisible galaxy lying along the line of sight. Quasar spectra, then, afford astronomers a means of probing previously undetected parts of the universe.

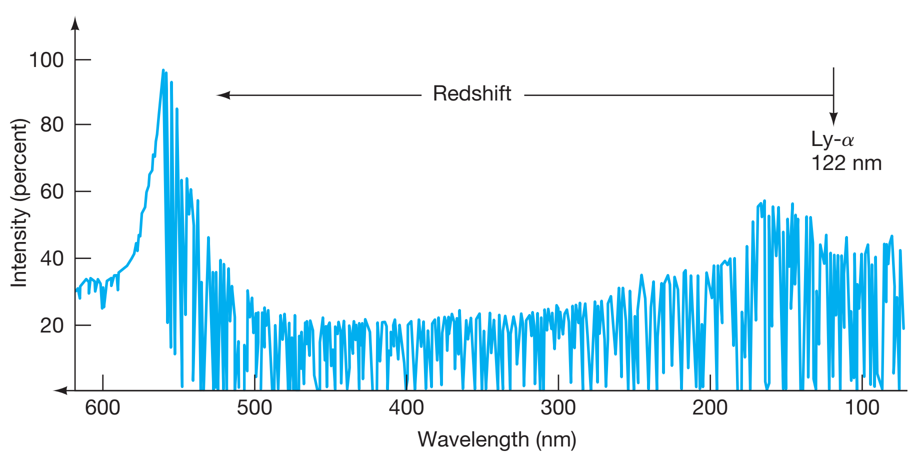
The absorption lines of atomic hydrogen are of particular interest, since hydrogen makes up so much of all matter in the cosmos. Specifically, hydrogen's ultraviolet (122 nm) "Lyman-alpha" line, associated with transitions between the ground and first excited states, is often used in this context. *(Sec. 2.6)* As illustrated in Figure 16.24, when astronomers observe the spectrum of a high-redshift quasar, they typically see a "forest" of absorption lines starting at the (redshifted) wavelength of the quasar's own Lyman-alpha emission line and extending to shorter wavelengths. These lines are interpreted as Lyman-alpha absorption features produced by gas clouds in foreground structures—galaxies, clusters, and so on—giving astronomers crucial information about the distribution of matter along the line of sight.

Quasar light thus explores an otherwise invisible component of cosmic gas. In principle, every intervening cloud of atomic hydrogen leaves its own characteristic imprint on the quasar's spectrum, in a form that lets us explore the distribution of matter in the universe. By comparing these *Lyman-alpha forests* with the results of simulations, astronomers hope to refine many key elements of the theories of galaxy formation and the evolution of large-scale structure.



▲ **FIGURE 16.23 The Universe on Larger Scales** This large-scale galaxy survey, carried out at the Las Campanas Observatory in Chile, consists of 23,697 galaxies within about 1000 Mpc, in two 80° (wide) × 4.5° (thick) wedges of the sky. Many voids and "walls" on scales of up to 100–200 Mpc are evident, but nothing much larger. For scale, the extent of the survey shown in Figure 16.22 is marked as a thin blue arc in the northern sky here.

MA INTERACTIVE
Quasar Spectrum due to Absorption from Distant Clouds



◀ **FIGURE 16.24 Absorption Line "Forest"** The huge number of absorption lines in the spectrum of quasar QSO 1422 + 2309 are the ultraviolet 122 nm Lyman-alpha lines from hundreds of clouds of foreground hydrogen gas, each redshifted by a slightly different amount (but less than the quasar itself). The peak at left marks the Lyman-alpha emission line from the quasar itself, emitted at 122 nm but redshifted here to 564 nm, in the visible range.

16.1 DISCOVERY

The Sloan Digital Sky Survey

Many of the photographs used in this book—not to mention most of the headline-grabbing imagery found in the popular media—come from large, high-profile, and usually very expensive, instruments such as NASA's *Hubble Space Telescope* and the European Southern Observatory's Very Large Telescope in Chile. ∞ *(Secs. 3.3, 3.4)* Their spectacular views of deep space have revolutionized our view of the universe, yet a less well-known, considerably cheaper, but no less ambitious, project begun in 2000 may, in the long run, have every bit as great an impact on astronomy and our understanding of the cosmos.

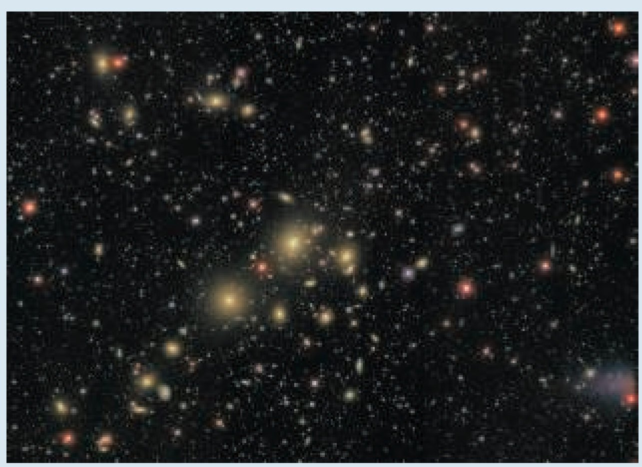
The Sloan Digital Sky Survey (SDSS) was originally a 5-year project, but it has been extended numerous times, most recently until 2020. It was designed to systematically map out a quarter of the entire sky on a scale and at a level of precision never before attempted. It cataloged almost 1 billion celestial objects, recording their apparent brightnesses at five different colors (wavelength ranges) spread across the optical part of the spectrum. In addition, spectroscopic follow-up observations determined redshifts and hence distances to 2 million galaxies and 500,000 quasars. These data have been used to construct even more detailed redshift surveys than those described in the text and to probe the structure of the universe on very large scales. The sensitivity of the survey was such that it could detect bright galaxies like our own out to distances of more than 1 billion parsecs. Very bright objects, such as quasars and young starburst galaxies, were detectable almost throughout the entire observable universe.

The first figure shows the Sloan Survey telescope, a special-purpose 2.5-m instrument sited in Apache Point Observatory, near Sunspot, New Mexico. The telescope is not space-based, does not employ active or adaptive optics, and cannot probe as deeply (i.e., far) into space as do larger instruments. How could it possibly compete with these other systems? The answer is that, unlike most other large telescopes in current use, where hundreds or even thousands of observers share the instrument and compete for its time, the SDSS telescope was designed specifically for the purpose of the survey. It has a wide field of view and was dedicated to the task, carrying out observations of the sky on *every* clear night during the duration of the project.

The survey used this single instrument night after night, applying tight quality controls on which nights' data are actually incorporated into the survey. Nights with poor seeing or other problematic conditions were discarded and the observations repeated. The end product was a database of exceptionally high quality and uniformity spanning an enormous volume of space—a monumental achievement and an indispensable tool for cosmology. The survey field of view covers much of the sky away from the Galactic plane in the north, together with a large swath of the sky around the Galactic south pole.

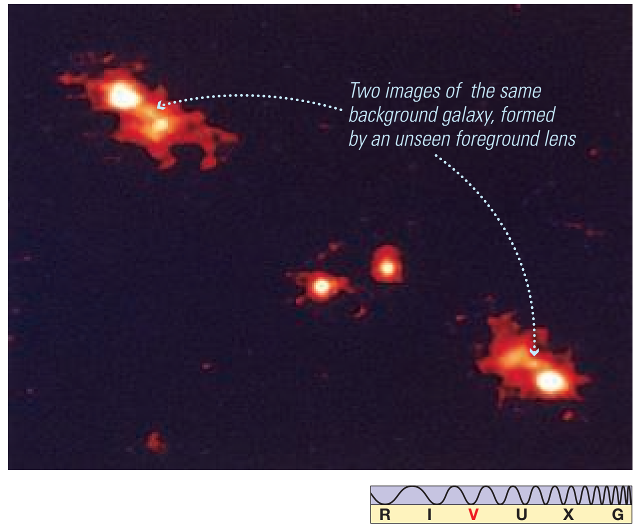
Archiving images and spectra on millions of galaxies produces a lot of data. The total amount of data gathered by the survey's 120-megapixel camera comprises more than 100 *trillion* bytes of high-quality data—far more than the entire Library of Congress! All of the survey data have now been released to the public. The second figure shows a nearby galaxy cluster with a giant elliptical at its center—one of hundreds of thousands of images that make up the full dataset. Among recent highlights, SDSS has detected the largest known structure in the universe, observed the most distant known galaxies and quasars, and has been instrumental in pinning down the key observational parameters describing our universe (see Chapter 17).

SDSS impacts astronomy in areas as diverse as the large-scale structure of the universe, the origin and evolution of galaxies, the nature of dark matter, the structure of the Milky Way, and the properties and distribution of interstellar matter and exoplanetary systems. Its uniform, accurate, and detailed database is likely to be used by generations of scientists for decades to come, and its success has spawned several much larger follow-up surveys; the most ambitious is due to become operational in 2021.



(SDSS; R. Lupton)

R I V U X G



▶ **FIGURE 16.25 Twin Quasar** This twin quasar (designated AC114 and located about 2 billion parsecs away) is not two separate objects at all. Instead, the two large "blobs" (at upper left and lower right) are images of the same object, created by a gravitational lens. The lensing galaxy itself is probably not visible in this image—the two objects near the center of the frame are thought to be unrelated galaxies in a foreground cluster. *(NASA)*

Quasar "Mirages"

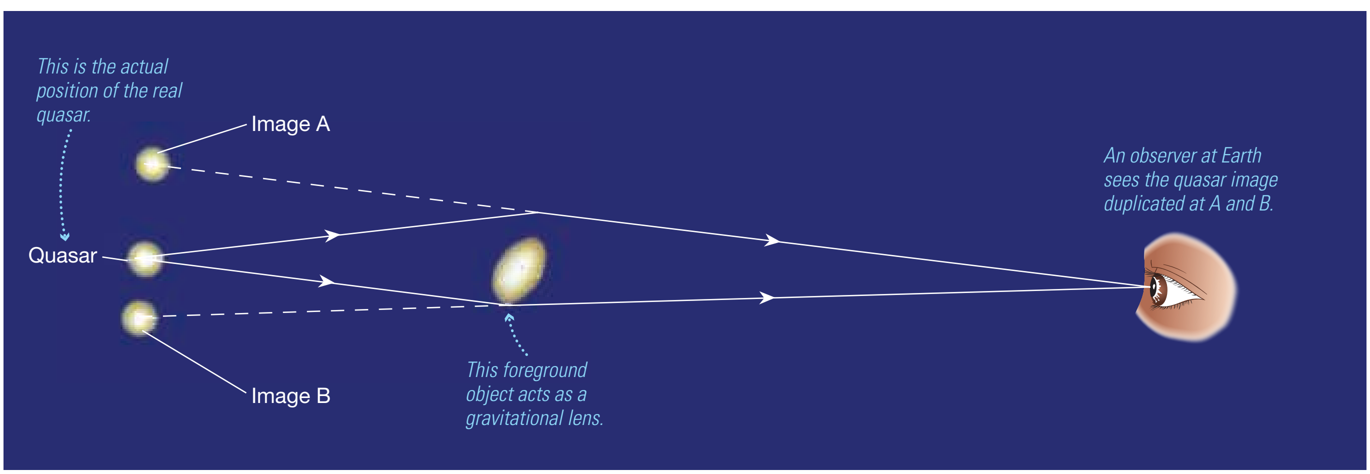
In 1979 astronomers were surprised to discover what appeared to be a binary quasar—two quasars with exactly the same redshift and very similar spectra, separated by only a few arc seconds on the sky. Remarkable as the discovery of such a binary would have been, the truth about this pair of quasars turned out to be even more amazing. Closer study of the quasars' radio emission revealed that they were *not* two distinct objects. Instead, they were two separate images of the *same* quasar! Optical views of such a *twin quasar* are shown in Figure 16.25.

What could produce such a "doubling" of a quasar image? The answer is gravitational lensing—the deflection and focusing of light from a background object by the gravity of some foreground body (Figure 16.26). In Chapter 14 we saw how lensing by compact objects in the halo of the Milky Way Galaxy may amplify the light from a distant star, allowing astronomers to detect otherwise invisible stellar dark matter. ∞ *(Sec. 14.6)* In the case of quasars, the idea is the same, except that the foreground lensing object is an entire galaxy or galaxy cluster and the deflection of the light is so great (a few arc seconds) that several separate images of the background object may be formed, as shown in Figure 16.27. About two dozen such gravitational lenses are known.

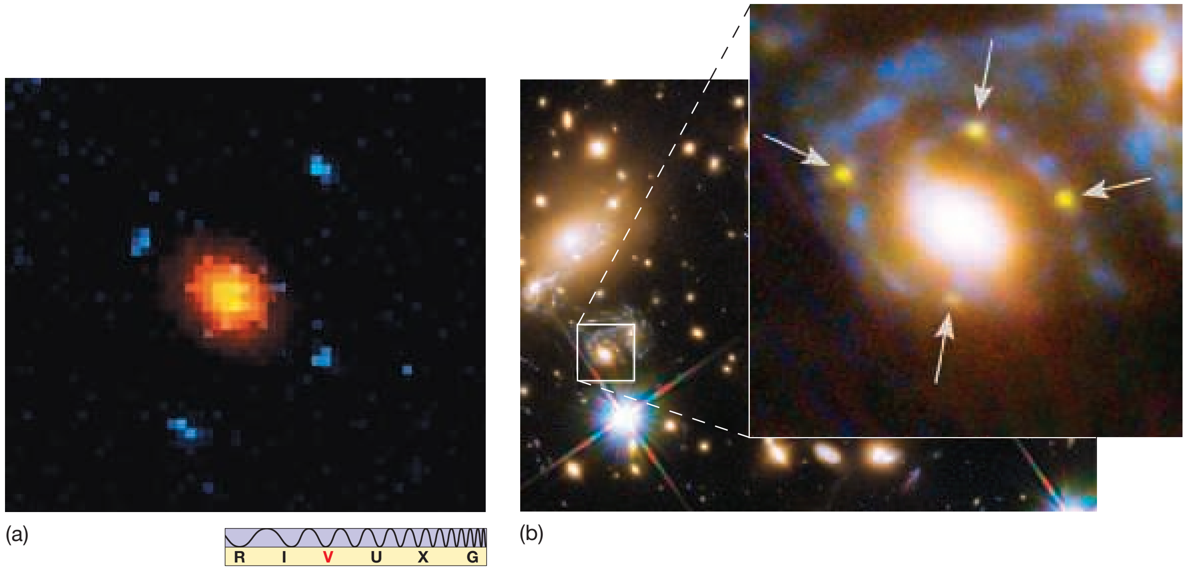
The existence of these multiple images provides astronomers with a number of useful observational tools. First, lensing by a foreground galaxy tends to amplify the light of the quasar, as just mentioned, making it easier to observe. At the same time, *microlensing* by individual stars within the galaxy may cause large fluctuations in the quasar's brightness, allowing astronomers to study the galaxy's stellar content.

Second, because the light rays forming the images usually follow paths of different lengths, there is often a time delay, ranging from days to years, between them. This delay provides advance notice of interesting events, such as sudden changes in the quasar's brightness—if one image flares up, in time the other(s) will too, giving astronomers a second chance to study the event. The time delay also allows astronomers to determine the distance to the lensing galaxy. This method provides an alternative means of measuring Hubble's constant that is independent of any of the techniques discussed previously. The average value of H_0 reported by workers using this approach is consistent with the 70 km/s/Mpc value used throughout this text.

▼ **FIGURE 16.26 Gravitational Lens INTERACTIVE** When light from a distant object passes close to a galaxy or cluster of galaxies along the line of sight, the image of the background object (here, the quasar) can sometimes be split into two or more separate images (A and B). The foreground object is a gravitational lens.



▶ **FIGURE 16.27 Einstein Cross**
(a) The Einstein Cross, a multiply-imaged quasar, spans only a couple of arc seconds, showing four separate images of the same quasar produced by the galaxy at the center. (b) This 2015 *Hubble* image shows four images (marked in the inset) of a supernova in a distant background galaxy some 3 billion parsecs away, due to lensing by a foreground galaxy and the cluster in which it resides. *(NASA)*



DATA POINTS

Scales in the Universe

More than 50 percent of students had difficulty ranking the scale of various objects in the universe. Some key points to bear in mind:

- Planets are smaller—and usually much smaller—than stars, but stars are in turn much smaller than the planetary systems that surround them. A typical planetary system is around 100 astronomical units across.
- Stars are born in star clusters, which are typically a few parsecs across, much larger than any planetary system orbiting a star.
- Stars and star clusters form galaxies, which might be anywhere from a few thousand to 100,000 parsecs across—much larger than stars, planetary systems, or star clusters.
- Galaxies themselves form larger groupings called galaxy clusters, typically a few million parsecs (a few megaparsecs) in size.
- On even larger scales, galaxies and clusters form superclusters, tens to hundreds of megaparsecs across.
- All of these scales are tiny compared to the size of the observable universe, which is roughly 10 billion parsecs, or 10,000 megaparsecs.

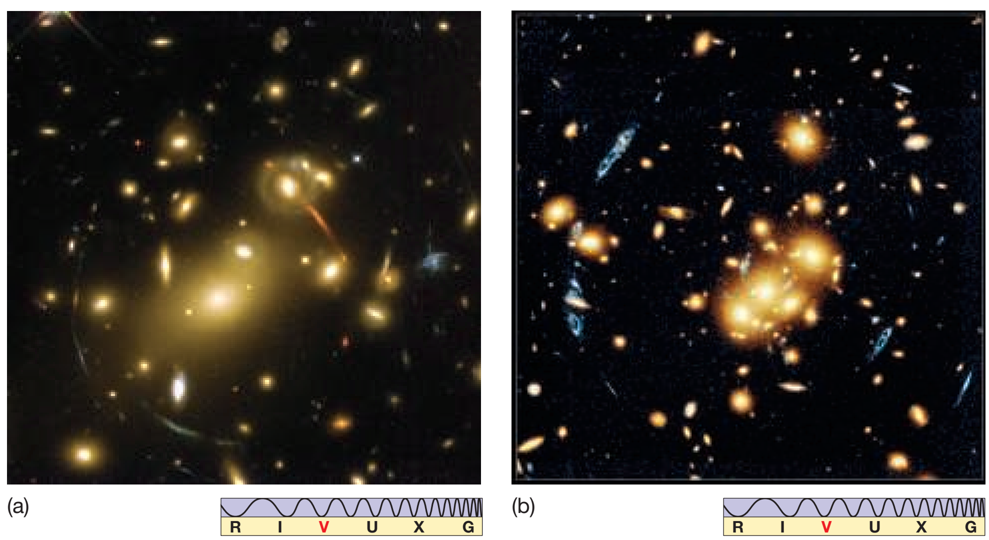
Mapping Dark Matter

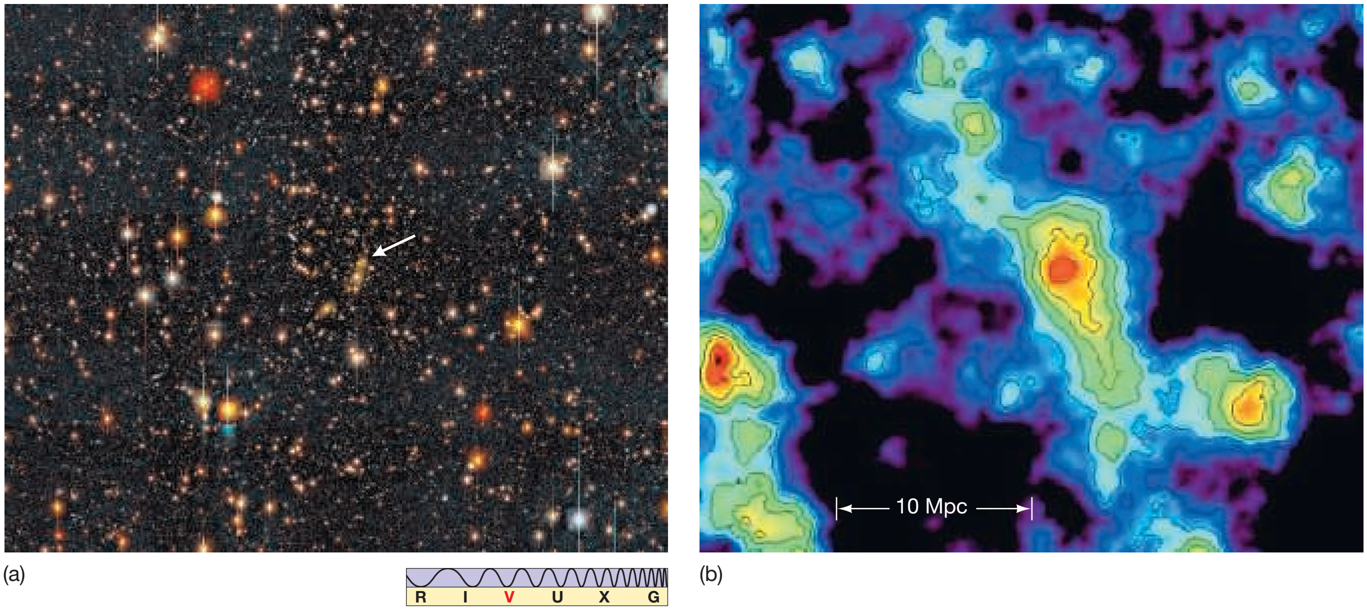
Astronomers have extended the ideas first learned from studies of quasars to use lensing of any distant object to probe the universe. Distant faint irregular galaxies—the raw material of the universe, if current theories are correct (see Section 16.4)—are of particular interest here, as they are far more common than quasars; thus, they provide much better coverage of the sky. By studying the lensing of background quasars and galaxies by foreground galaxy clusters, astronomers can obtain a better understanding of the distribution of dark matter on large scales.

Figures 16.28(a) and (b) show how the images of faint, background galaxies are bent into arcs by the gravity of a foreground galaxy cluster. The degree of bending allows the total mass of the cluster (including the dark matter) to be measured. The (mostly blue) loop- and arc-shaped features visible in Figure 16.28(b) are multiple images of a single, distant (unseen) spiral or ring-shaped galaxy, lensed by the foreground galaxy cluster (the yellow-red blobs in the image).

It is even possible to reconstruct the foreground dark mass distribution by carefully analyzing the distortions of the background objects, providing a means of tracing out the distribution of matter on scales far larger than have previously been possible Figure 16.29(a) is an optical image of a (hard to see) foreground galaxy

▶ **FIGURE 16.28 Galaxy Cluster Lensing**
INTERACTIVE (a) This spectacular example of gravitational lensing shows more than a hundred faint arcs from very distant galaxies. The wispy pattern spread across the foreground galaxy cluster (A2218, about a billion parsecs distant) is caused by A2218's gravitational field, which deflects the light from background galaxies and distorts their appearance. (b) Another galaxy cluster, known only by its catalog name 0024 + 1654 and residing some 1.5 billion pc away, shows reddish-yellow blobs that are mostly normal elliptical galaxies and bluish loop-like features that are images of a single background galaxy. *(NASA)*





(a) (b)

▲ **FIGURE 16.29 Dark Matter Map** By measuring distortions in the images of background objects, astronomers can make maps of dark matter in the universe. Analysis of an optical view (a) of a region of the sky containing a small galaxy cluster (the clump of yellowish galaxies near the center of the frame indicated by the arrow) reveals the distribution of dark matter (b) in and near the visible cluster and on the same scale as (a). *(J. A. Tyson, Bell Labs; Alcatel-Lucent; NOAO)*

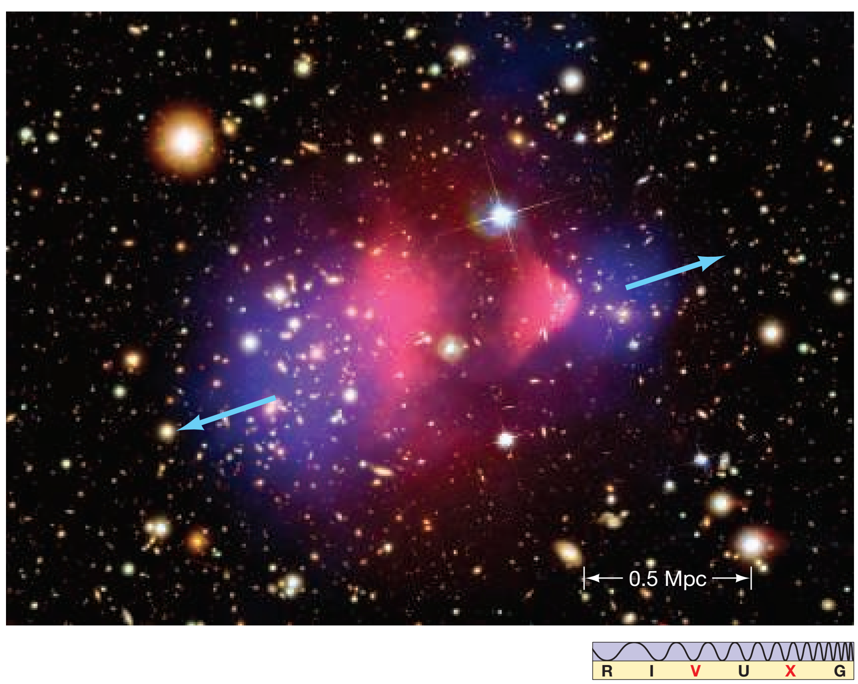
cluster set against a background of much fainter distant galaxies. Figure 16.29(b) is the reconstructed dark-matter image, revealing the presence of dark mass many megaparsecs from the cluster center, extending far beyond the visible galaxies. Evidently, the dark matter fraction is even greater on supercluster scales than it is on the scales of individual galaxies or galaxy clusters. Notice also the elongated structure of the dark-matter distribution, reminiscent of the Virgo Supercluster and filamentary structure seen in large-scale galaxy surveys. ∞ *(Sec. 14.5)*

Astronomers have used these techniques to obtain what may be the first direct observational evidence for dark matter. Figure 16.30 shows combined optical

MA ANIMATION/VIDEO
Simulation of Gravitational Lens in Space

MA ANIMATION/VIDEO
The Cosmic Web of Dark Matter

The arrows indicate the directions in which the two clusters are now moving, subsequent to what might have been the most energetic collision in the universe since the Big Bang.



◀ **FIGURE 16.30 Cluster Collision** **INTERACTIVE** Clusters of galaxies must also occasionally collide, as is apparently the case here for this combined cluster with the innocuous name 1E 0657-56 and the nickname "bullet cluster." This is a composite image of a region about 1 billion parsecs away, showing optical light from the galaxies themselves in white and X-ray emission from the hot intracluster gas in red. By contrast, the blue color represents the inferred dark matter within the two large clusters that is distinctly displaced from their normal matter. *(NOAO/NASA)* and X-ray images of a distant galaxy cluster called 1E 0657-56. The fuzzy red region shows the location of the hot X-ray–emitting gas in the system, the dominant *luminous* component of the mass. The blue regions indicate where most of the mass actually lies, as determined from lensing studies of background galaxies. Note that the bulk of the mass is *not* found in the form of hot gas, implying that the dark matter is distributed differently from the "normal" matter in the cluster.

The explanation for this odd state of affairs is that we are witnessing a collision between two clusters. Each initially contained hot gas and dark matter distributed throughout the cluster, but when the two collided, the pressure of each gas cloud effectively stopped the other, leaving the gas behind in the middle as the galaxies and dark matter moved on. This separation between the gas and the dark matter directly contradicts some alternative theories of gravity that have been invoked to avoid the "dark matter problem" in galaxies and clusters and may prove to be a crucial piece of evidence in our understanding of large-scale structure in the universe.

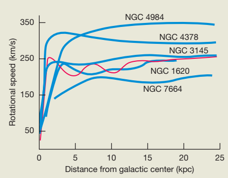
THE BIG QUESTION

What is dark matter? Is it actual matter that exerts a gravitational pull but is impossible to detect by electromagnetic means, or does it imply that something is badly wrong with our theoretical understanding of the way gravity works on very large scales? Dark matter—and dark energy, too (see Chapter 17)—represent the foremost scientific conundrums in astronomy today, and whoever solves them will become immediately famous. How will science resolve these cosmic mysteries, and what new mysteries will arise as a result?

CHAPTER REVIEW

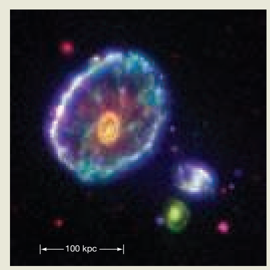
SUMMARY

LO1 The masses of nearby spiral galaxies can be determined by studying their rotation curves. Astronomers also use studies of binary galaxies and distant galaxy clusters to obtain statistical mass estimates of the galaxies involved.

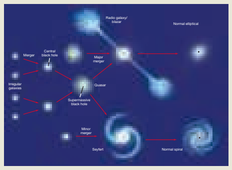


LO2 Measurements of galaxy and cluster masses reveal the presence of large amounts of dark matter. The fraction of dark matter grows as the scale under consideration increases. More than 90 percent of the mass in the universe is dark. Substantial quantities of hot X-ray–emitting gas have been detected among the galaxies in many clusters, but not enough to account for the dark matter inferred from dynamical studies.

LO3 Researchers know of no simple evolutionary sequence that links spiral, elliptical, and irregular galaxies. Most astronomers think that large galaxies formed by the merger of smaller ones and collisions and mergers of galaxies play very important roles in galactic evolution. A starburst galaxy may result when a galaxy has a close encounter or a collision with a neighbor. The strong tidal distortions caused by the encounter compress galactic gas, resulting in a widespread burst of star formation. Mergers between spirals most likely result in elliptical galaxies.

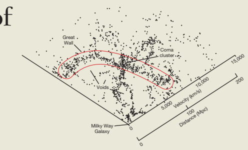


LO4 Quasars, active galaxies, and normal galaxies may represent an evolutionary sequence. When galaxies began to form and



merge, conditions may have been suitable for the formation of large black holes at their centers, and highly luminous quasars could have been the result. The brightest quasars consume so much fuel that their energy-emitting lifetimes must be quite short. As the fuel supply diminished, the quasar dimmed, and the galaxy in which it was embedded became intermittently visible as an active galaxy. At even later times, the nucleus became virtually inactive, and a normal galaxy was all that remained. Many normal galaxies have been found to contain central massive black holes, suggesting that most galaxies in clusters have the capacity for activity if they should interact with a neighbor.

LO5 Galaxy clusters themselves tend to clump together into **superclusters** (p. 463). The Virgo Cluster, the Local Group, and several other nearby clusters form the Local Supercluster. On even larger scales, galaxies and galaxy clusters are arranged on the surfaces of enormous "bubbles" of matter surrounding vast low-density regions called **voids** (p. 464). The origin of this structure is thought to be closely related to conditions in the very earliest epochs of the universe.



LO6 Quasars can be used as probes of the universe along the line of sight. Some quasars have been observed to have double or multiple images. These result from gravitational lensing, in which the gravitational field of a foreground galaxy or galaxy cluster bends and focuses the light from the more distant quasar. Analysis of the images of distant galaxies, distorted by the gravitational effect of a foreground cluster, provides a means of determining the masses of galaxy clusters—including the dark matter—far beyond the information that optical images of the galaxies themselves afford.

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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** Describe two techniques for measuring the mass of a galaxy.
2. **LO2** Why do astronomers think that galaxy clusters contain more mass than we can see?
3. Why do some clusters of galaxies emit X-rays?
4. What evidence do we have that galaxies collide with one another?
5. **LO3** Describe the role of collisions in the formation and evolution of galaxies.
6. **POS** Do you think that collisions between galaxies constitute "evolution" in the same sense as the evolution of stars? Why or why not?
7. What are starburst galaxies, and what do they have to do with galaxy evolution?
8. Why do astronomers think that quasars represent an early stage of galactic evolution?
9. **LO4** **POS** Why does the theory of galaxy evolution suggest that there should be supermassive black holes at the centers of many normal galaxies?
10. What evidence do we have for supermassive black holes in galaxies?
11. How might a normal galaxy become active?
12. What is a redshift survey?
13. **LO5** What are voids? What is the distribution of galactic matter on very large (more than 100 Mpc) scales?
14. **LO6** **POS** How can observations of distant quasars be used to probe the space between us and them?
15. **POS** How can astronomers "see" dark matter?

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

1. Intergalactic gas in galaxy clusters emits large amounts of energy in the form of radio waves. (T/F)
2. Distant galaxies appear to be much larger than those nearby. (T/F)
3. Collisions between galaxies are rare and have little or no effect on the stars and interstellar gas in the galaxies involved. (T/F)
4. The quasar stage of a galaxy ends because the central black hole swallows up all the matter around it. (T/F)
5. Elliptical galaxies may be formed by mergers between spirals. (T/F)
6. The fact that a typical quasar would consume an entire galaxy's worth of mass in 10 billion years suggests that quasar lifetimes are relatively long. (T/F)
7. On the largest scales, galaxies in the universe appear to be arranged on huge sheets surrounding nearly empty voids. (T/F)
8. The image of a distant quasar can be split into several images by the gravitational field of a foreground cluster. (T/F)
9. A galaxy containing substantial amounts of dark matter will (a) appear darker; (b) spin faster; (c) repel other galaxies; (d) have more tightly wound arms.
10. According to X-ray observations, the space between galaxies in a galaxy cluster is (a) completely devoid of matter; (b) very cold; (c) very hot; (d) filled with faint stars.
11. The fraction of mass of the universe made up of dark matter is (a) zero; (b) less than 10 percent; (b) roughly 50 percent; (d) more than 90 percent.
12. In current theories of galaxy evolution, quasars occur (a) early in the evolutionary sequence; (b) near the Milky Way; (c) when elliptical galaxies merge; (d) late in the evolutionary sequence.
13. Many nearby galaxies (a) may be much more active in the future; (b) contain quasars; (c) have radio lobes; (d) may have been much more active in the past.
14. **VIS** If light from a distant quasar did not pass through any intervening atomic hydrogen clouds, then Figure 16.24 (Absorption Line "Forest") would have to be redrawn to show (a) more absorption features; (b) fewer absorption features; (c) a single, large absorption feature; (d) more features at short wavelengths, but fewer at long wavelengths.
15. **VIS** If Figure 16.26 (Gravitational Lens) were to be redrawn using a more massive lensing galaxy, the quasar images would be (a) farther apart; (b) closer together; (c) fainter; (d) redder.

PROBLEMS

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

1. ■ Two galaxies orbit one another at a separation of 500 kpc. Their orbital period is estimated to be 30 billion years. Use Kepler's third law to find the total mass of the pair. ∞ ***(Sec. 14.6)***
2. ■ Based on the data in Figure 16.1, estimate the mass of the galaxy NGC 4984 inside 20 kpc.
3. ■■■ A small satellite galaxy is moving in a circular orbit around a much more massive parent and just happens to be moving exactly parallel to the line of sight as seen from Earth. The recession velocities of the satellite and the parent galaxy are measured to be 6450 km/s and 6500 km/s, respectively, and the two galaxies are separated by an angle of 0.1° on the sky. Assuming H_0 = 70 km/s/Mpc, calculate the mass of the parent galaxy.
4. ■ Calculate the average speed of hydrogen nuclei (protons) in a gas of temperature 20 million K. ∞ ***(More Precisely 5-1)*** Compare this with the speed of a galaxy moving in a circular orbit of radius 1 Mpc around the center of a cluster of mass 10^{14} solar masses.
5. ■ In a galaxy collision, two similar-sized galaxies pass through each other with a combined relative velocity of 1500 km/s. If each galaxy is 100 kpc across, how long does the event last?
6. ■■ A certain quasar has a redshift of 0.25 and an apparent magnitude of 13. Using the data from Table 15.2, calculate the quasar's absolute magnitude and hence its luminosity. ∞ ***(More Precisely 10-1)*** Compare the apparent brightness of the quasar, viewed from a distance of 10 pc, with that of the Sun as seen from Earth.
7. ■ What are the absolute magnitude and luminosity of a quasar with a redshift of 5 and an apparent magnitude of 22?
8. ■■ Assuming an energy-generation efficiency (that is, the ratio of energy released to total mass-energy consumed) of 20 percent, calculate how long a 10^{40}-W quasar can shine if a total of 10^8 solar masses of fuel is available.
9. ■■ The spectrum of a quasar with a redshift of 0.20 contains two sets of absorption lines, redshifted by 0.15 and 0.155, respectively. If H_0 = 70 km/s/Mpc, estimate the distance between the intervening galaxies responsible for the two sets of lines.
10. ■■■ Light from a distant quasar is deflected through an angle of 3″ by an intervening lensing galaxy and is subsequently detected on Earth (see Figure 16.26). If Earth, the galaxy, and the quasar are all aligned, the quasar's redshift is 3.0 (see Table 15.2), and the galaxy lies midway between Earth and the quasar, calculate the minimum distance between the light ray and the center of the galaxy.

ACTIVITIES

Collaborative

1. Figure 16.10 is called the Hubble Deep Field. It contains too many galaxies for one person to easily count. Each group member should count the galaxies in a random area 2 cm $\times$ 2 cm and then determine a group average. Since the entire image is approximately 500 cm^2, multiply your group's average number of galaxies in a 2 cm $\times$ 2 cm area by 125 to estimate the number of galaxies in the image. How does your value compare to that of another group?

Individual

1. Look for a copy of the *Atlas of Peculiar Galaxies* by Halton Arp. It is available in book form, but it will be more convenient to find a version online. Search for examples of interacting galaxies of various types: (1) tidal interactions, (2) starburst galaxies, (3) collisions between two spirals, and (4) collisions between a spiral and an elliptical. For (1) look for galactic material pulled away from a galaxy by a neighboring galaxy. Is the latter galaxy also tidally distorted? In (2) the surest signs of starburst activity are bright knots of star formation. In what type(s) of galaxies do you find starburst activity? For (3) and (4) how do collisions differ depending on the types of galaxies involved? What typically happens to a spiral galaxy after a near miss or collision? Do ellipticals suffer the same fate?

17

Cosmology

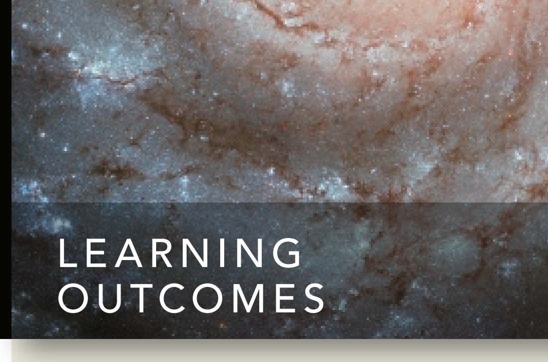
The Big Bang and the Fate of the Universe

Our field of view now extends for billions of parsecs into space and billions of years back in time. We have asked and answered many questions about the structure and evolution of planets, stars, and galaxies. At last we are in a position to address the central issues of the biggest puzzle of all: How big is the universe? How long has it been around, and how long will it last? What was its origin, and what will be its fate? What is it made of? Many cultures have asked these questions, in one form or another, and have developed their own cosmologies—theories about the nature, origin, and destiny of the universe—to answer them. In this chapter, we see how modern scientific cosmology addresses these important issues and what it has to tell us about the universe we inhabit. After more than 10,000 years of civilization, science may be ready to provide some insight into the ultimate origin of all things.

THE BIG PICTURE

Cosmology is the study of the origin, structure, evolution, and fate of the universe on the largest scales, yet one of its key predictions is that the entire cosmos can be traced back to an extraordinarily hot and dense energy state billions of years ago. As mind-boggling as it may seem, all that we see around us apparently arose from microscopic "quantum" fluctuations that occurred a fraction of a second after the Big Bang. Ironically, the largest structures observed today are inextricably tied to the smallest scales known in physics.

◂ The universe began in a fiery expansion some 14 billion years ago, and out of this maelstrom emerged all the energy that would later form galaxies, stars, and planets. The story of the origin, evolution, and fate of all these systems comprises the subject of cosmology. This image—called the Ultra Deep Field—was taken with the Advanced Camera for Surveys aboard the *Hubble* telescope. More than a thousand galaxies are crowded into this one image, displaying many different types and shapes. In all, astronomers estimate that the observable universe contains about 100 billion such galaxies. *(NASA/ESA)*



LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** State the cosmological principle, and explain its significance and observational underpinnings.
- **LO2** Describe the Big Bang theory of the expanding universe, and explain why the night sky is dark.
- **LO3** Outline the factors that determine whether the universe will expand forever, and explain the connection between the density of the universe and the overall geometry of space.
- **LO4** Describe the observational evidence that the expansion of the universe is accelerating, and discuss the role of dark energy in that acceleration.
- **LO5** Identify the cosmic microwave background as a major piece of evidence in favor of the Big Bang theory, and explain how it formed.
- **LO6** Explain how nuclei and atoms emerged from the primeval fireball and why astronomers think most of the helium observed in the universe was not formed by nuclear fusion in stars.
- **LO7** Summarize the horizon and flatness problems, and describe how the theory of cosmic inflation solves them.
- **LO8** Describe the formation of large-scale structure in the cosmos, and present observational evidence for the leading theory of structure formation.

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17.1 The Universe on the Largest Scales

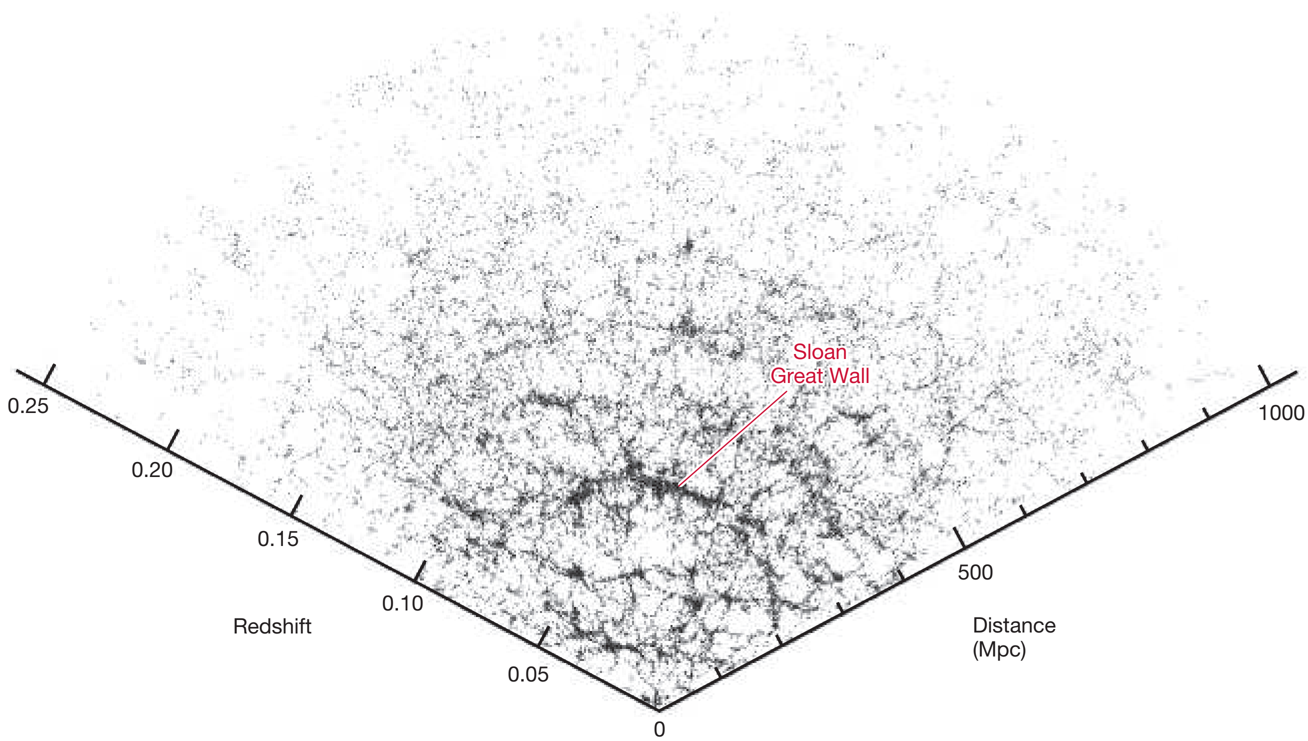
Galaxy surveys have revealed the existence of structures in the universe up to 200 Mpc across. *(Sec. 16.5)* Are there even larger structures? Does the hierarchy of clustering of stars into galaxies and galaxies into galaxy clusters, superclusters, voids, and filaments continue forever, on larger and larger scales? Perhaps surprisingly, given the trend we have just described, most astronomers think the answer is *no*.

We saw in Chapter 16 how astronomers use redshift surveys to construct three-dimensional maps of the universe on truly "cosmic" scales. *(Sec. 16.5)* Figure 17.1 is a map similar to those shown previously, but based on data from the most extensive redshift survey to date—the Sloan Digital Sky Survey. *(Discovery 16-1)* It extends out to a distance of almost 1000 Mpc, comparable to Figure 16.23, but because it includes much fainter galaxies, the Sloan map contains many more galaxies than the earlier figure, making structure easier to discern, particularly at large distances. Many voids and filaments can be seen on scales of a few tens of megaparsecs, but on the largest scales, apart from the general falloff in numbers of galaxies at large distances—basically because more distant galaxies are harder to see due to the inverse-square law—there is no obvious evidence for any structures on scales larger than about 200 Mpc. *(Sec. 10.2)* Careful statistical analysis of the galaxy distribution confirms this impression—even the Sloan Great Wall in Figure 17.1 can be explained statistically as a chance superposition of smaller structures.

The results of this and other large-scale surveys strongly suggest that the universe is **homogeneous** (the same everywhere) on scales greater than a few hundred megaparsecs. In other words, if we took a huge cube—300 Mpc on a side, say—and placed it anywhere in the universe, its overall contents would look much the same no matter where it was centered. The universe also appears to be **isotropic** (the same in all directions) on these scales. Excluding directions that

CONCEPT CHECK

In what sense is the universe homogeneous and isotropic?



▲ **FIGURE 17.1 Galaxy Survey** This map of the universe is drawn using data from the Sloan Digital Sky Survey. *(Discovery 16-1)* It shows the locations of 66,976 galaxies lying within 12 degrees of the celestial equator and extending to a distance of almost 1000 Mpc (or a redshift of about 0.25). The largest known structure in the universe, the Sloan Great Wall, stretches nearly 300 Mpc across the center of the frame. *(SDSS Collaboration)* are obscured by our Galaxy, we count roughly the same number of galaxies per square degree in any patch of the sky we choose to observe, provided we look deep (far) enough that local inhomogeneities don't distort our sample.

In the science of **cosmology**—the study of the structure and evolution of the entire universe—researchers generally assume that the universe is homogeneous and isotropic on sufficiently large scales. No one knows if these assumptions are precisely correct, but we can at least say that they are consistent with current observations. In this chapter we simply assume that they hold. The twin assumptions of homogeneity and isotropy are known as the **cosmological principle**.

The cosmological principle has some very far-reaching implications. For example, it implies that there can be no *edge* to the universe because that would violate the assumption of homogeneity. And there can be no *center* because then the universe would not look the same in all directions from any noncentral point, violating the assumption of isotropy. This is the familiar Copernican principle expanded to truly cosmic proportions—not only are we not central to the universe, but *no one* can be central, because *the universe has no center*!

17.2 The Expanding Universe

Every time you go outside at night and notice that the sky is dark, you are making a profound cosmological observation. Here's why.

Olbers's Paradox

Let's assume for a moment that, in addition to being homogeneous and isotropic, the universe is also infinite in spatial extent and unchanging in time. On average, then, the universe is uniformly populated with galaxies filled with stars. In that case, as illustrated in Figure 17.2, when you look up at the night sky, your line of sight must *eventually* encounter a star. The star may lie at an enormous distance, in some remote galaxy, but the laws of probability dictate that, sooner or later, any line drawn outward from Earth will run into a bright stellar surface.

Faraway stars appear fainter than those nearby because of the inverse-square law, but they are also much more numerous—the number of stars we see at any given distance in fact increases as the *square* of the distance (just consider the area of a sphere of increasing radius). ∞ *(Sec. 10.2)* Thus the diminishing brightnesses of distant stars are exactly balanced by their increasing numbers, and stars at all distances contribute equally to the total amount of light received on Earth.

This fact has a dramatic implication: No matter where you look, the sky should be as bright as the surface of a star—the entire night sky should be as brilliant as the surface of the Sun! The obvious difference between this prediction and the actual appearance of the night sky is known as **Olbers's paradox**, after the 19th-century German astronomer Heinrich Olbers, who popularized the idea.

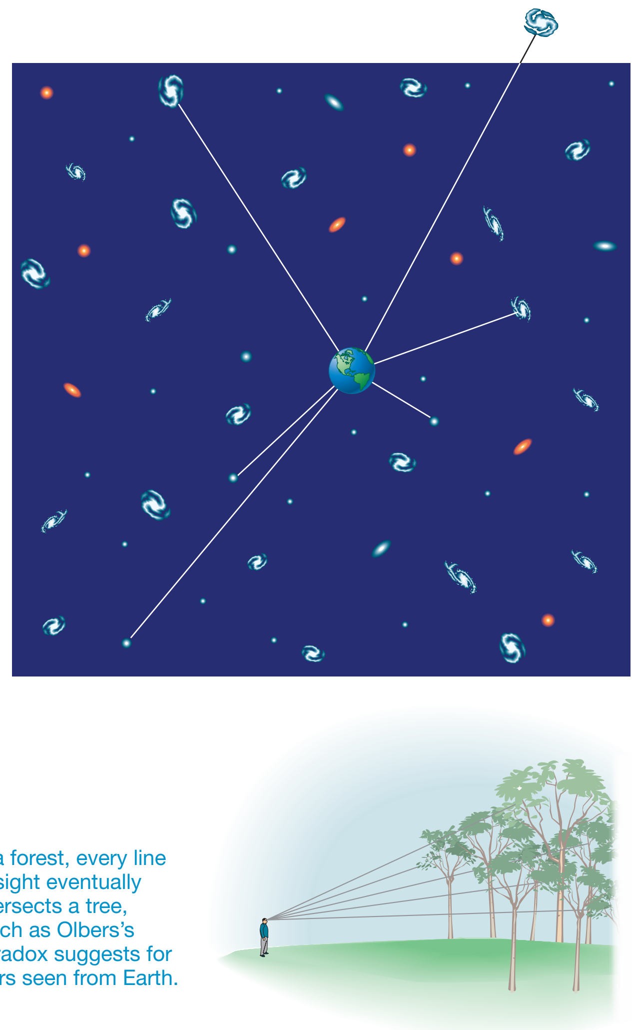
So why is the sky dark at night? Given that the universe is homogeneous and isotropic, then one (or both) of the other two assumptions must be false. Either the universe is finite in extent, or it evolves in time. In fact, the answer involves a little of each and is intimately tied to the behavior of the universe on the largest scales.

The Birth of the Universe

We have seen that all the galaxies in the universe are rushing away from us as described by Hubble's law:

$$\text{recession velocity} = H_0 \times \text{distance},$$

where we take Hubble's constant H_0 to be 70 km/s/Mpc. ∞ *(Sec. 15.3)* We have used this relationship as a convenient means of determining the distances to galaxies and quasars, but it is much more than that.



▲ **FIGURE 17.2 Olbers's Paradox** If the universe were homogeneous, isotropic, infinite in extent, and unchanging, then any line of sight from Earth should eventually meet a star and the entire night sky should be bright. This obvious contradiction of the facts is known as Olbers's paradox.

Assuming that all velocities have remained constant in time, we can ask how long it has taken for any given galaxy to reach its present distance from us. The answer follows from Hubble's law. The time taken is simply the distance traveled divided by the velocity:

$$\begin{aligned} \text{time} &= \frac{\text{distance}}{\text{velocity}} \\ &= \frac{\text{distance}}{H_0 \times \text{distance}} \qquad \text{(using Hubble's law for the velocity)} \\ &= \frac{1}{H_0}. \end{aligned}$$

For $H_0 = 70$ km/s/Mpc, this time is about 14 billion years. Notice that it is *independent* of the distance—galaxies twice as far away are moving twice as fast, so the time they took to cross the intervening distance is the same.

Hubble's law therefore implies that, at some time in the past—14 billion years ago, according to the foregoing simple calculation (see also Section 17.4)—*all* the galaxies in the universe lay right on top of one another. In fact, astronomers think that *everything* in the universe—matter and radiation alike—was confined at that instant to a single point of enormously high temperature and density. Then the universe began to expand at a furious rate, its density and temperature falling rapidly as the volume increased. This stupendous, unimaginably violent event, involving literally everything in the cosmos, is known as the **Big Bang**. Astronomers often refer to the superhot, expanding universe just after the Big Bang as the primeval fireball. It marked the beginning of the universe.

The Big Bang provides the resolution of Olbers's paradox. Whether the universe is actually finite or infinite in extent is irrelevant, at least as far as the appearance of the night sky is concerned. The key point is that we see only a *finite* part of it—the region lying within roughly 14 billion light-years of us. What lies beyond is unknown—its light has not had time to reach us.

Where Was the Big Bang?

Now we know *when* the Big Bang occurred. Is there any way of telling *where*? Astronomers think that the universe is the same everywhere, yet we have just seen that the observed recession of the galaxies described by Hubble's law suggests that all the galaxies expanded from a point at some time in the past. Wasn't that point, then, different from the rest of the universe, violating the assumption of homogeneity expressed in the cosmological principle? The answer is a definite *no*!

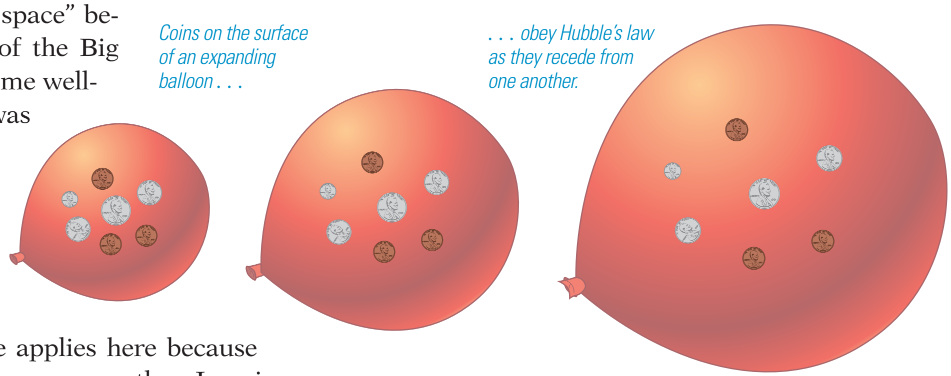
To understand why there is no center to the expansion, we must make a great leap in our perception of the universe. If the Big Bang was simply an enormous explosion that spewed matter out into space, ultimately to form the galaxies we see, then the foregoing reasoning would be quite correct. The universe would have a center and an edge, and the cosmological principle would not apply. But the Big Bang was *not* an explosion in an otherwise featureless, empty universe. The only way that we can have Hubble's law *and* retain the cosmological principle is to realize that the Big Bang involved the entire universe—not just the matter and radiation within it, but the universe *itself*. In other words, the galaxies are not flying apart into the rest of the universe. The universe itself is expanding. Like raisins in a loaf of raisin bread that move apart as the bread expands in an oven, the galaxies are just along for the ride.

INTERACTIVE MA
The Expanding Raisin Cake (Universe)

Let's reconsider some of our earlier statements in this new light. We now recognize that Hubble's law describes the expansion of the universe itself. Apart from small-scale individual random motions, galaxies are not moving with respect to the fabric of space. The component of the galaxies' motion that makes up the Hubble flow is really an expansion of space itself. The expanding universe remains homogeneous at all times. There is no "empty space" beyond the galaxies into which they rush. At the time of the Big Bang, the galaxies did not reside at a point located at some well-defined place within the universe. The *entire universe* was a point. The Big Bang happened *everywhere* at once.

To illustrate these ideas, imagine an ordinary balloon with coins taped to its surface, as shown in Figure 17.3. (Better yet, do the experiment yourself.) The coins represent galaxies, and the two-dimensional surface of the balloon represents the "fabric" of our three-dimensional universe. The cosmological principle applies here because every point on the balloon looks pretty much the same as every other. Imagine yourself as a resident of one of the coin "galaxies" on the leftmost balloon, and note your position relative to your neighbors. As the balloon inflates (that is, as the universe expands), the other galaxies recede from you and more distant galaxies recede more rapidly.

Regardless of which galaxy you chose to consider, you would see all the other galaxies receding from you, but nothing is special or peculiar about this fact. There is no center to the expansion and no position that can be identified as the location from which the universal expansion began. Everyone sees an overall expansion described by Hubble's law, with the same value of Hubble's constant in all cases. Now imagine letting the balloon deflate, running the "universe" backward from the present time to the moment of the Big Bang. *All* the galaxies (coins) would arrive at the same place at the same time at the instant the balloon reached zero size, but no single point on the balloon could be said to be *the* place where that occurred.



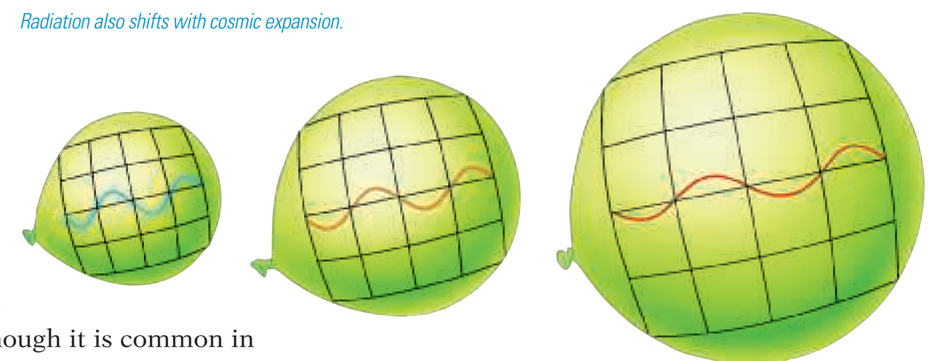
▲ **FIGURE 17.3 Receding Galaxies INTERACTIVE** Coins taped to the surface of a spherical balloon recede from each other as the balloon inflates (left to right). Similarly, galaxies recede from each other as the universe expands. As the coins separate, the distance between any two of them increases, and the rate of increase of this distance is proportional to the distance between them.

PROCESS OF SCIENCE CHECK

Why does Hubble's law imply a Big Bang?

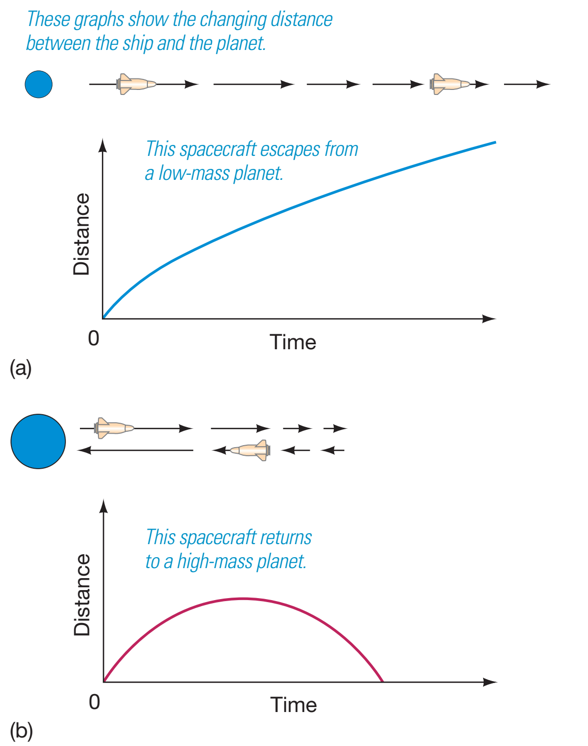
The Cosmological Redshift

Up to now, we have explained the cosmological redshift of galaxies as a Doppler shift, a consequence of their motion relative to us. ∞ *(Sec. 15.3)* However, we have just argued that the galaxies are not moving with respect to the universe, in which case the Doppler interpretation cannot be correct. The true explanation is that, as a photon moves through space, its wavelength is influenced by the expansion of the universe. Think of the photon as being attached to the expanding fabric of space, so its wavelength expands along with the universe, as illustrated in Figure 17.4. Although it is common in astronomy to refer to the cosmological redshift in terms of recessional velocity, bear in mind that, strictly speaking, this is not the right thing to do. The cosmological redshift is a consequence of the changing size of the universe and is *not* related to velocity at all.



▲ **FIGURE 17.4 Cosmological Redshift INTERACTIVE** As the universe expands, photons of radiation are stretched in wavelength, giving rise to the cosmological redshift.

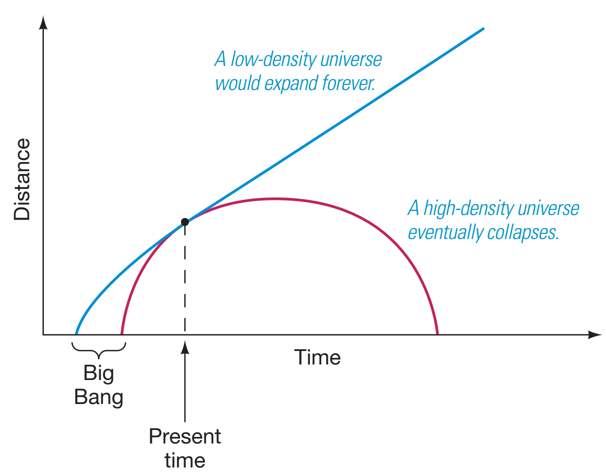
The redshift of a photon measures the amount by which the universe has expanded since that photon was emitted. For example, when we measure the light from a quasar to have a redshift of 7, it means that the observed wavelength is 8 times (1 plus the redshift) greater than the wavelength at the time of emission, which means that the light was emitted at a time when the universe was just one-eighth its present size (and we are observing the quasar as it was at that time). ∞ ***(More Precisely 15-1)*** In general, the larger a photon's redshift, the smaller the universe was at the time the photon was emitted and so the longer ago that emission occurred. Because the universe expands with time and redshift is related to that expansion, cosmologists routinely use redshift as a convenient means of expressing time.



▲ **FIGURE 17.5 Escape Speed** (a) A spacecraft (arrow) leaving a planet (blue ball) with a speed greater than the planet's escape speed follows an unbound trajectory and escapes. (b) If the launch speed is less than the escape speed, the ship eventually drops back to the planet. Its distance, as graphed, first rises and then falls.

CONCEPT CHECK

What are the two basic possibilities for the future expansion of the universe?



▲ **FIGURE 17.6 Model Universes** Distance between two galaxies as a function of time in each of the two basic universes discussed in the text: a low-density universe that expands forever and a high-density cosmos that collapses. The point where the two curves touch represents the present time.

17.3 Cosmic Dynamics and the Geometry of Space

Will the universe expand forever? This fundamental question about the fate of the universe has been at the heart of cosmology since Hubble's law was first discovered. Until the late 1990s, the prevailing view among cosmologists was that the answer would most likely be found by determining the extent to which gravity would slow, and perhaps ultimately reverse, the current expansion. However, it now appears that the answer is rather more subtle—and perhaps a lot more profound in its implications—than was hitherto thought.

Two Futures

Consider a rocket ship launched from the surface of a planet. What are the likely outcomes of the its motion? According to Newtonian mechanics, there are just two basic possibilities, depending on the launch speed of the ship relative to the escape speed of the planet. ∞ ***(More Precisely 5-1)*** If the launch speed is high enough, it will exceed the planet's escape speed, and the ship will never return to the surface. The speed will diminish because of the planet's gravitational pull, but it will never reach zero. The spacecraft leaves the planet on an unbound trajectory, as illustrated in Figure 17.5(a). Alternatively, if the launch speed is lower than the escape speed, the ship will reach a maximum distance from the planet and then fall back to the surface. Its bound trajectory is shown in Figure 17.5(b).

Similar reasoning applies to the expansion of the universe. Imagine two galaxies at some known distance from one another, their present relative velocity given by Hubble's law. The same two basic possibilities exist for these galaxies as for our rocket ship. The distance between them can increase forever, or it can increase for a while and then start to decrease. What's more, the cosmological principle says that whatever the outcome, it must be the same for *any* two galaxies—in other words, the same statement applies to the universe *as a whole*. Thus, as illustrated in Figure 17.6, the universe has only two options: It can continue to expand forever, or the present expansion will someday stop and turn around into a contraction. The two curves in the figure are drawn so that they pass through the same point at the present time. Both are possible descriptions of the universe, given its current size and expansion rate.

What determines which of these possibilities will actually occur? In the case of a rocket ship of fixed launch speed, the *mass* of the planet determines whether or not escape will occur—a more massive planet has a higher escape speed, making it less likely that the rocket can escape. For the universe, the corresponding quantity is the *density* of the cosmos. A high-density universe contains enough mass to stop the expansion and eventually cause a recollapse. Such a universe is destined ultimately to shrink toward a superdense, superhot singularity much like the one from which it originated—a "Big Crunch." A low-density universe, conversely, will expand forever. In that case, in time, even with the most powerful telescopes, we will see no galaxies in the sky beyond the Local Group (which is not itself expanding). The rest of the observable universe will appear dark, the distant galaxies too faint to be seen.

The dividing line between these outcomes—the density corresponding to a universe in which *gravity acting alone* would be just sufficient to halt the present expansion—is called the universe's **critical density**. For $H_0 = 70$ km/s/Mpc, the critical density is about 9×10^{-27} kg/m^3. That's an extraordinarily low density—just five hydrogen atoms per cubic meter, a volume the size of a typical household closet. In more "cosmological" terms, it corresponds to about 0.1 Milky Way Galaxy (including the dark matter) per cubic megaparsec.

We will see in a moment that the separation between never-ending expansion and cosmic collapse is not nearly as straightforward as the foregoing simple reasoning would suggest. Several independent lines of evidence now indicate that gravity is *not* the only influence on the dynamics of the universe on large scales (Section 17.4). As a result, while the "futures" just described are still the only two possibilities for the long-term evolution of the universe, the distinction between them turns out to be more than just a matter of density alone. Nevertheless, the density of the universe—or, more precisely, the *ratio of the total density to the critical value*—is a vitally important quantity in cosmology.

The Shape of the Universe

We have reverted to the familiar notions of Newtonian mechanics and gravity and moved away from general relativity and the more correct concept of warped spacetime, because speaking in Newtonian terms makes our discussion of the evolution of the universe easier to understand. ∞ ***(Secs. 1.4, 13.5)*** However, general relativity makes some predictions about the universe that do not have a simple description within Newton's theory.

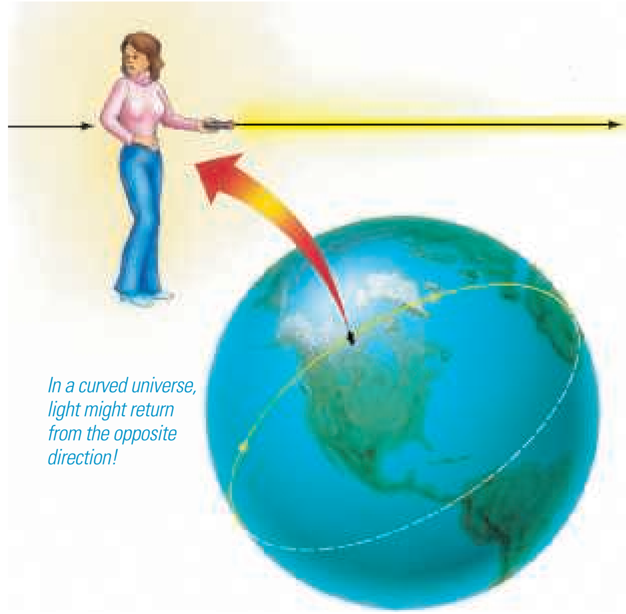
Foremost among these non-Newtonian predictions is the fact that space is curved and that the degree of curvature is determined by the total density of the cosmos. ∞ ***(Sec. 13.5)*** But general relativity is clear on what "density" means here. Both matter *and* energy must be taken into account, with energy (E) properly "converted" into mass (m) units via Einstein's famous relation $E = mc^2$. ∞ ***(More Precisely 13-1)*** The density of the universe includes not just the atoms and molecules that make up the familiar normal matter around us, but also the invisible dark matter that dominates the masses of galaxies and galaxy clusters, as well as *everything* that carries energy—photons, relativistic neutrinos, gravity waves, and anything else we can think of.

In a homogeneous universe, the curvature (on sufficiently large scales) must be the same everywhere, so there are really only three distinct possibilities for the large-scale geometry of space. General relativity tells us that the geometry of the universe depends only on the ratio of the density of the universe to the critical density (as defined in the previous section). Cosmologists call the ratio of the universe's actual density to the critical value the *cosmic density parameter* and denote it by the symbol Ω_0 ("omega nought"). In terms of this quantity, then, a universe with density equal to the critical value has $\Omega_0 = 1$, a "low-density" cosmos has Ω_0 less than 1, and a "high-density" universe has Ω_0 greater than 1.

In a high-density universe (Ω_0 greater than 1), space is curved so much that it bends back on itself and closes off, making the universe *finite* in size. Such a universe is known as a **closed universe**. It is difficult to visualize a three-dimensional volume uniformly arching back on itself in this way, but the two-dimensional version is well known: It is the surface of a sphere, like the balloon we discussed earlier. Figure 17.3, then, is the two-dimensional likeness of a three-dimensional closed universe. Like the surface of a sphere, a closed universe has no boundary, yet it is finite in extent.[1] One remarkable property of a closed universe is illustrated in Figure 17.7: A flashlight beam shining in some direction in space might eventually traverse the entire universe and return from the opposite direction.

The surface of a sphere curves, loosely speaking, "in the same direction" no matter which way we move from a given point. A sphere is said to have *positive curvature*. However, if the density of the universe is below the critical value, then the curvature of space is qualitatively quite different from that of a sphere. The two-dimensional surface corresponding to such a space curves like a saddle and is said to have *negative curvature*. Most people have seen a saddle—it curves "up" in

[1]Notice that for the sphere analogy to work, we must imagine ourselves as two-dimensional "flatlanders" who cannot visualize or experience in any way the third dimension perpendicular to the sphere's surface. Flatlanders are confined to the sphere's surface, just as we are confined to the three-dimensional volume of our universe.



▲ **FIGURE 17.7 Einstein's Curve Ball** In a closed universe, a beam of light launched in one direction might return someday from the opposite direction after circling the universe, just as motion in a "straight line" on Earth's surface will eventually encircle the globe.

CONCEPT CHECK

How is the curvature of space related to the size and density of the universe?

one direction and "down" in another, but no one has ever seen a uniformly negatively curved surface, for the good reason that it cannot be constructed in three-dimensional space! It is just "too big" to fit. A low-density (Ω_0 less than 1) saddle-curved universe is infinite in extent and is usually called an **open universe**.

The intermediate case, when the density is precisely equal to the critical density (i.e., $\Omega_0 = 1$), is the easiest to visualize. This **critical universe** has no curvature. It is said to be "flat," and it is infinite in extent. In this case, and only in this case, the geometry of space on large scales is precisely the familiar Euclidean geometry taught in high school. Apart from its overall expansion, this is basically the universe that Newton knew.

17.4 The Fate of the Cosmos

Is there any way for us to determine which of the futures just described actually applies to our universe (apart from just waiting to find out)? Will the universe end as a small, dense point much like that from which it began? Or will it expand forever? And can we hope to determine the geometry of the vast cosmos we inhabit? Finding answers to these questions has been the dream of astronomers for decades. We are fortunate to live at a time when we can subject these questions to intensive observational tests and come up with definite answers—even though they aren't what most cosmologists expected! Let's begin by looking at the density of the universe (or, equivalently, the cosmic density parameter Ω_0).

The Density of the Universe

How might we determine the average density of the universe? On the face of it, it would seem simple—just measure the average mass of the galaxies residing within a large parcel of space, calculate the volume of that space, and compute the total mass density. When astronomers do this, they usually find a little less than 10^{-28} kg/m^3 in the form of luminous matter. Largely independent of whether the chosen region contains only a few galaxies or a rich galaxy cluster, the resulting density is about the same, within a factor of 2 or 3. Galaxy counts thus yield a value of Ω_0 of only a few percent. If that measure were correct, and galaxies were all that existed, then we would live in a low-density open universe destined to expand forever.

But there is a catch. Most of the matter in the universe is *dark*—it exists in the form of invisible material that has been detected only through its gravitational effect in galaxies and galaxy clusters. ∞ ***(Secs. 14.6, 16.1)*** We currently do not know *what* the dark matter is, but we *do* know that it is there. Galaxies may contain as much as 10 times more dark matter than luminous material, and the figure for galaxy clusters is even higher—perhaps as much as 95 percent of the total mass in clusters is invisible. Even though we cannot see it, dark matter contributes to the average density of the universe and plays its part in opposing the cosmic expansion. Including all the dark matter that is known to exist in galaxies and galaxy clusters increases the value of Ω_0 to about 0.25.

Although we can detect and quantify the effects of dark matter in galaxies and galaxy clusters, its distribution on larger scales is harder to measure. Astronomers have developed techniques to study matter on supercluster and larger scales, using gravitational lensing of distant objects and the large-scale motions of galaxies and clusters to probe the gravitational fields of cosmic clumps of invisible matter. ∞ ***(Sec. 16.5)*** Yet all these studies add little to the overall density. As best we can tell, there doesn't seem to be much additional dark matter "tucked away" on very large scales. Most cosmologists agree that the overall density of matter (luminous plus dark) in the universe is between 25 and 30 percent of the critical value—not enough to halt the universe's current expansion.

Cosmic Acceleration

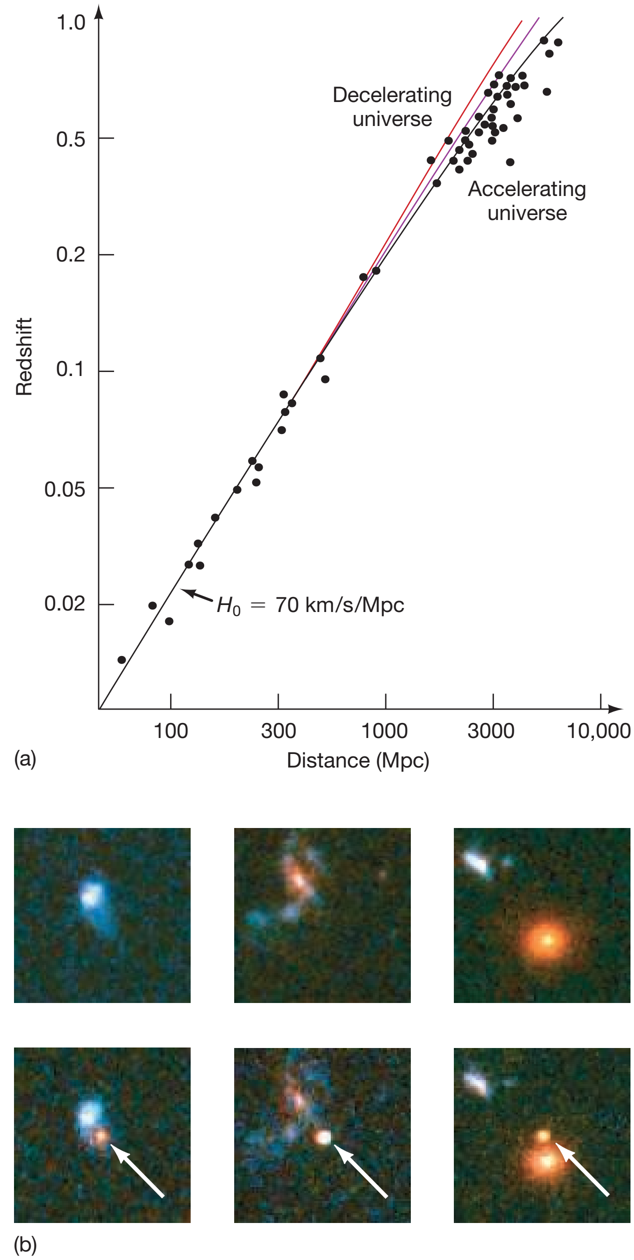
Determining the density of the universe is an example of a *local* measurement that provides an estimate of Ω_0. But the result we obtain depends on just how local our measurement is, and there are many uncertainties in the result, especially on large scales. In an attempt to get around this problem, astronomers have devised alternative methods that rely instead on *global* measurements, covering much larger regions of the observable universe. In principle, such global tests should indicate the universe's overall density, not just its value in our cosmic neighborhood.

One such global method is based on observations of Type I (carbon detonation) supernovae. *(Sec. 12.5)* Recall that these objects are both very bright and have a remarkably narrow spread in luminosities, making them particularly useful as standard candles. *(Sec. 15.2)* They can be used as probes of the universe because, by measuring their distances (*without* using Hubble's law) and their redshifts, we can determine the rate of cosmic expansion in the distant past. Here's how the method works.

Suppose the universe is decelerating, as we would expect if gravity were slowing its expansion. Then, because the expansion rate is decreasing, objects at great distances—that is, objects that emitted their radiation long ago—should appear to be receding *faster* than Hubble's law predicts. Figure 17.8 illustrates this concept. If the universal expansion were constant in time, recessional velocity and distance would be related by the black line in the figure. (The line is not quite straight because it takes the expansion of the universe properly into account in computing the distance.) *(More Precisely 15-1)* In a decelerating universe, the velocities of distant objects should lie *above* the black curve, and the deviation from that curve is greater for a denser universe in which gravity has been more effective at slowing the expansion.

How does theory compare with reality? In the late 1990s two groups of astronomers announced the results of independent, systematic surveys of distant supernovae. Some of these supernovae are shown in Figure 17.8(b); the data are marked on Figure 17.8(a). Far from clarifying the picture of cosmic deceleration, however, these findings indicated that the expansion of the universe is not slowing, but actually accelerating! According to the supernova data, galaxies at large distances are receding *less* rapidly than Hubble's law would predict. The deviations from the decelerating curves appear small in the figure, but they are statistically very significant, and both groups report similar findings.

These observations are *inconsistent* with the standard "gravity only" Big Bang theory just described and sparked a major revision of our view of the cosmos. The measurements are difficult, and the results depend quite sensitively on just how "standard" the supernovae luminosities really are. Not surprisingly, since so much hangs on this result, the reliability of the supernova measurement technique has been the subject of intense scrutiny by cosmologists. However, no convincing argument against the method has yet been put forward, so there is no reason to believe that we are somehow being "fooled" by nature. As far as we can tell, the measurements are good, and the cosmic acceleration is real. This unexpected but crucially important result earned the leaders of the two groups who discovered it the 2011 Nobel Prize in Physics.



▲ FIGURE 17.8 **Accelerating Universe** (a) In a decelerating universe (purple and red curves), redshifts of distant objects are greater than would be predicted from Hubble's law (black curve). The reverse is true for an accelerating universe. The data points show observations of some 50 supernovae that strongly suggest cosmic expansion is accelerating. (b) The bottom frames show three Type I supernovae (marked by arrows) that exploded in distant galaxies when the universe was nearly half its current age. The top frames show the same areas prior to the explosions. *(CfA/NASA)*

Dark Energy

What could cause an overall acceleration of the universe? Frankly, cosmologists don't know, although several possibilities have been suggested. Whatever it is, the mysterious cosmic force causing the universe to accelerate is neither matter nor radiation. Although it carries energy, it exerts an overall *repulsive* effect on the universe, causing empty space to expand. It has come to be known simply as **dark energy**, and it is perhaps *the* leading puzzle in astronomy today.

17.1 DISCOVERY

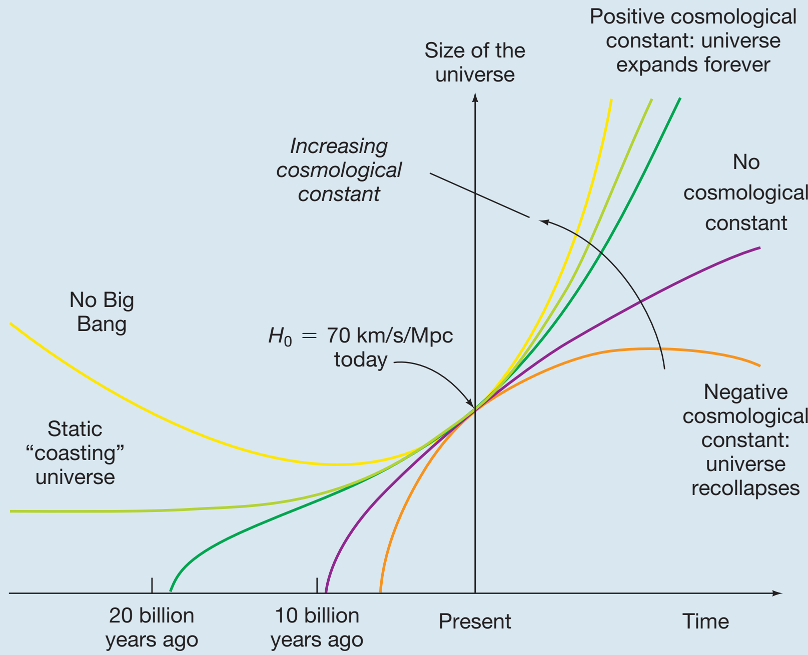
Einstein and the Cosmological Constant

Even the greatest minds are fallible. The first scientist to apply general relativity to the universe was (not surprisingly) the theory's inventor, Albert Einstein. When he derived and solved the equations describing the behavior of the universe, Einstein discovered that they predicted a universe that evolved in time. But in 1917 neither he nor anyone else knew about the expansion of the universe, as described by Hubble's law, which would not be discovered for another 10 years. ∞ *(Sec. 15.3)* At the time Einstein, like most scientists, believed that the universe was static—that is, unchanging and everlasting. The discovery that there was no static solution to his equations seemed to Einstein a near-fatal flaw in his new theory.

To bring his theory into line with his beliefs, Einstein tinkered with his equations, introducing a "fudge factor" now known as the cosmological constant. The accompanying figure shows the effect of introducing a cosmological constant into the equations describing the expansion of a critical-density universe. One possible solution is a "coasting" universe, whose radius does indeed remain constant for an indefinite period of time. Einstein took this to be the static universe he expected. Instead of predicting an evolving cosmos, which would have been one of general relativity's greatest triumphs, Einstein yielded to a preconceived notion of the way the universe "should be," unsupported by observational evidence. Later, when the expansion of the universe was discovered and Einstein's equations—without the cosmological constant—were found to describe it perfectly, he declared that the cosmological constant was the biggest mistake of his scientific career.

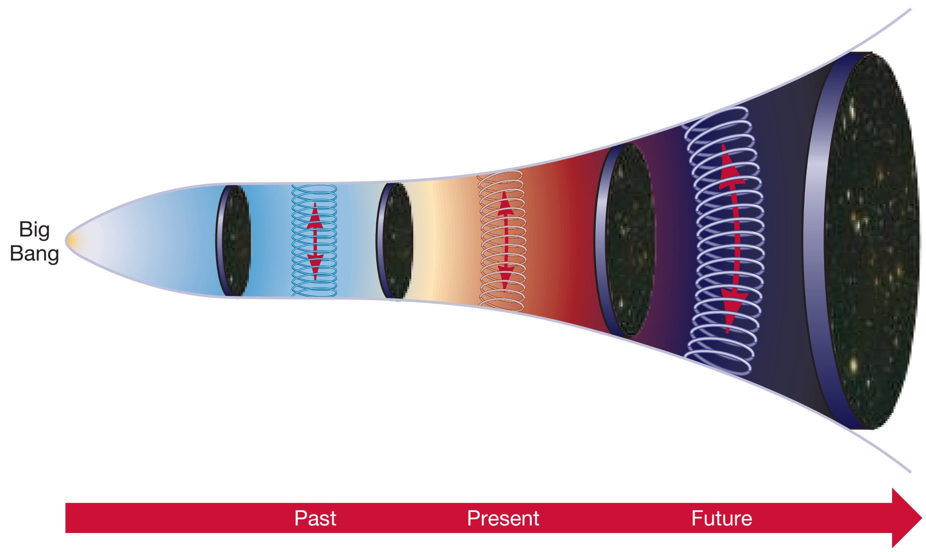
For many researchers—Einstein included—the main problem with the cosmological constant was (and still is) the fact that it had no clear physical interpretation. Einstein introduced it to fix what he thought was a problem with his equations, but he discarded it immediately once he realized that no problem actually existed. Scientists are very reluctant to introduce unknown quantities into their equations purely to make the results "come out right." As a result, the cosmological constant fell out of favor among astronomers for many years. However, as described in the text, it has apparently been completely rehabilitated and is now identified as a leading candidate for the "dark energy" whose existence is inferred from studies of the universe on very large scales.

Attempts are underway to construct theories of dark energy that preserve the character of the cosmological constant, yet also account for its value in some natural way, perhaps somehow coupling it to the density of matter. Before we make too many sweeping statements about the role of the cosmological constant in cosmology, we should probably remember the experience of its inventor and bear in mind that—at least for now—its physical meaning remains completely unknown.



As illustrated in Figure 17.9, the repulsive effect of dark energy is proportional to the size of the universe, so it increases as the universe expands. Thus, it was negligible at early times, but today it is the major factor controlling the cosmic expansion. Furthermore, since the effect of gravity *weakens* as the expansion proceeds, it follows that once dark energy begins to dominate, gravity can never catch up, and the universe will continue to accelerate at an ever-increasing pace. Thus, by opposing the attractive force of gravity, the repulsive effect of dark energy strengthens our earlier conclusion that the universe will expand forever.

A leading candidate for dark energy is an additional "vacuum pressure" force associated with empty space and effective only on very large scales. Known simply as the **cosmological constant,** it has a long and checkered history (see *Discovery 17-1*) and has gone in and out of favor since its invention by Einstein



◀ FIGURE 17.9 **Dark Energy** The expansion of the universe is opposed by the attractive force of gravity and sped up by the repulsion due to dark energy. As the universe expands, the gravitational force weakens, whereas the force due to dark energy increases. A few billion years ago, dark energy began to dominate, and the expansion of the cosmos has been accelerating ever since.

almost a century ago. Note, however, that while models including the cosmological constant can fit the observational data, astronomers as yet have no clear physical interpretation of what it actually means—it is neither required nor explained by any known law of physics.

The fact that the present value of the repulsive dark energy force is comparable to the attractive force of gravity poses another problem to astronomers. When we calculate the evolution of a universe governed by a cosmological constant, consistent with current observations (see Figure 17.12), we find that this state of affairs was not true in the early universe (when galaxies were forming, say), nor will it be true in 10 or 20 billion years' time. In other words, the observations seem to suggest that we live at a special time in the history of the universe—a conclusion viewed with great suspicion by astronomers schooled in the Copernican principle. ∞ *(Sec. 1.1)* Cosmologists have tried to address this problem by constructing alternative theories in which the behavior of dark energy depends on the densities of matter and radiation in the universe, but for now at least, the cosmological constant seems to give just as good a fit to the observational data.

Cosmic Composition

In addition to measurements of density and acceleration, astronomers have several other means of estimating the "cosmological parameters" that describe the large-scale properties of our universe. Theoretical studies of the very early universe (Section 17.7) strongly suggest that the geometry of the universe should be precisely flat—and hence the density should be exactly critical. These ideas first became widespread in the 1980s and for many years seemed to be at odds with observations indicating a cosmic matter density of just 20–30 percent of the critical value, even taking the dark matter into account. The cosmic acceleration just discussed actually resolves that conflict, albeit at the price of introducing yet another unknown component—dark energy—into the cosmic mix.

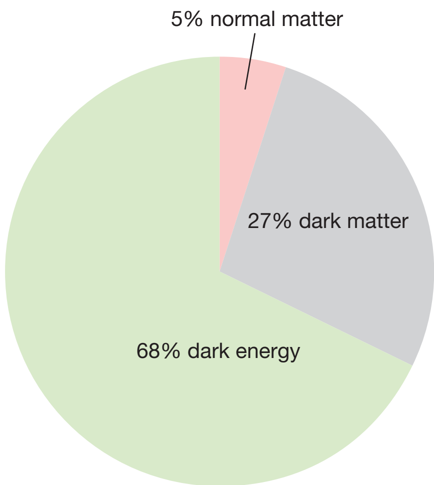
Detailed measurements of the radiation field known to fill the entire cosmos (Sections 17.5 and 17.8) support the theoretical prediction of critical density and are also consistent with the dark energy inferred from the supernova studies. Further support comes from careful analysis of galaxy surveys such as those discussed in Section 17.1, which allow astronomers to measure the growth of large-scale structure in the universe, and in turn to constrain the value of Ω_0.

Remarkably, all the approaches just described yield consistent results! The current consensus among cosmologists is that the universe is of precisely critical

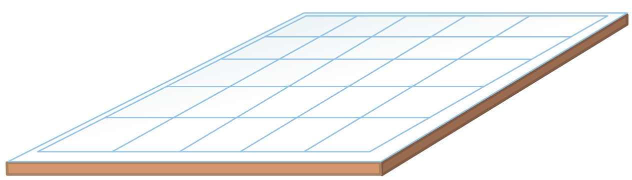
MA ANIMATION/VIDEO
Gravitational Curvature of Space

PROCESS OF SCIENCE CHECK

Why have astronomers concluded that dark energy is the major constituent of the universe?



▲ **FIGURE 17.10 Composition of the Universe** The universe today is made mostly of mysterious dark energy, accounting for nearly three-quarters of the total. Dark matter accounts for over a quarter. Normal matter amounts to only a few percent—and of that 3.6% is mostly in galactic and intergalactic gas, and only a miniscule 0.4% comprises stars, planets, and life-forms.



▲ **FIGURE 17.11 Geometry of the Universe** The universe on the largest scales seems geometrically flat—governed by the same familiar Euclidean geometry taught in high schools.

density, $\Omega_0 = 1$, but this density is made up of both matter (mostly dark) and dark energy (suitably converted into mass units using the relation $E = mc^2$). ∞ *(Sec. 9.5)* Note that, while dark energy *opposes* the force of gravity in its effect on cosmic expansion, it still *adds* to the total density (and Ω_0) in its effect on the curvature of space. Based on all available data, as illus- trated in Figure 17.10, the best estimate is that matter accounts for 32 percent of the total and dark energy for the remaining 68 percent. This is the assumption underlying Table 15.1 and used consistently throughout this book. ∞ *(More Precisely 15-1)*

Note that such a universe will expand forever and, the heavy machinery of general relativity and curved spacetime notwithstanding, is perfectly flat (Figure 17.11)—an irony that would no doubt have amused Newton!

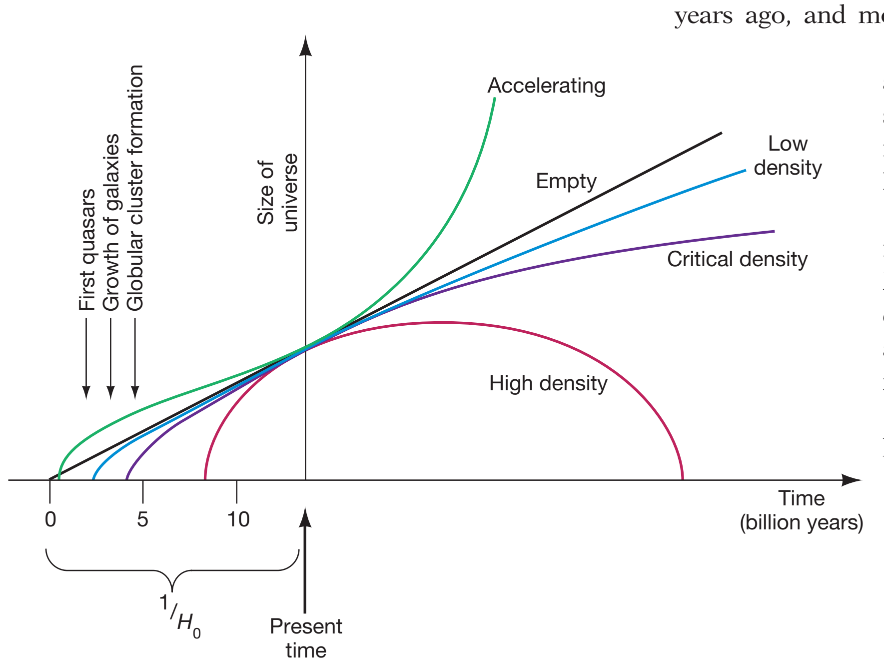
The Age of the Universe

In Section 17.2, when we estimated the age of the universe from the accepted value of Hubble's constant, we made the assumption that the expansion speed of the cosmos was constant in the past. However, as we have just seen, this is a considerable oversimplification. Gravity tends to slow the universe's expansion, while dark energy acts to accelerate it. In the absence of a cosmological constant, the universe expanded faster in the past than it does today, so the assumption of a constant expansion rate leads to an overestimate of the universe's age—such a universe is younger than the 14 billion years calculated earlier. Conversely, the repulsive effect of dark energy tends to increase the age of the cosmos.

Figure 17.12 illustrates these points. It is similar to Figure 17.6, except that here we have added three curves, including one (labeled "Empty") corresponding to a constant expansion rate at the present value and another to an accelerating universe with the "best estimate" parameters given above. The age of a critical-density universe with no cosmological constant (whose curve is also added here) is about 9 billion years. A low-density, unbound universe is older than 9 billion years but still less than 14 billion years old. The age corresponding to the accelerating universe is about 14 billion years, coincidentally very close to the value calculated for constant expansion.

How does this compare with an age estimated by other means? On the basis of the theory of stellar evolution, the oldest globular clusters formed about 12 billion years ago, and most are estimated to be between 10 and 12 billion years old. ∞ *(Sec. 12.6)* This range is indicated on Figure 17.12. These ancient star clusters are thought to have formed at around the same time as our Galaxy, so they date the epoch of galaxy formation. More important, they can't be older than the universe! Figure 17.12 shows that globular cluster ages are consistent with a 14 billion-year-old cosmos, and even allow a couple of billion years for galaxies to grow, as discussed in Chapter 16. ∞ *(Sec. 16.3)* Note also that the cluster ages are *not* consistent with a critical-density universe without dark energy. This independent check of a key prediction is an important piece of evidence supporting the modern version of the Big Bang theory.

Thus, for $H_0 = 70$ km/s/Mpc, our current best guess of the history of the universe places the Big Bang at 14 billion years



◄ **FIGURE 17.12 Cosmic Age** The age of a universe without dark energy (represented by all three lower curves colored red, purple, and blue) is always less than $1/H_0$ and decreases for larger values of the present-day density. The existence of a repulsive cosmological constant (green curve) increases the age of the cosmos.

ago. The first quasars appeared about 13 billion years ago (at a redshift of 7), the peak quasar epoch (redshifts 2–3) occurred during the next 1 billion years, and the oldest known stars in our Galaxy formed during the 2 billion years after that. ∞ *(Sec. 16.3)* Even though astronomers do not presently understand the nature of dark energy, the good agreement between so many separate lines of reasoning has convinced many that the dark-matter/dark-energy Big Bang theory just described is the correct description of the universe.

Bear in mind as we proceed through the remainder of this chapter that the Big Bang *is* a scientific theory and as such is continually being challenged and scrutinized. ∞ *(Sec. 0.5)* It makes testable predictions about the state and history of the cosmos and must change—or fail—if these predictions are found to be at odds with observations. Astronomers aren't ready to relax just yet—the history of this subject suggests that there may be a few more unexpected twists and turns in the road before the details are finally resolved.

CONCEPT CHECK

Why do astronomers think the universe will expand forever?

17.5 The Early Universe

We now turn from studies of the far future of our universe to the quest to understand its distant past. Just how far back in time can we probe? Is there any way to study the universe beyond the most remote quasar? How close can we come to perceiving directly the edge of time, the very origin of the universe?

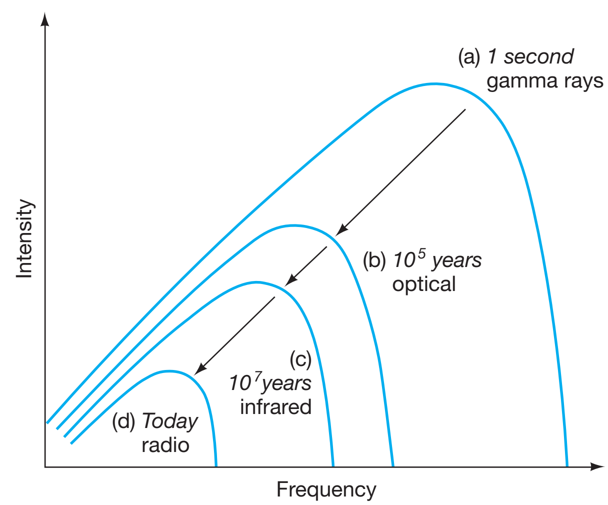
The Cosmic Microwave Background

A partial answer to these questions was discovered by accident in 1964, during an experiment designed to improve America's telephone system. As part of a project to identify and eliminate unwanted interference in satellite communications, Arno Penzias and Robert Wilson, scientists at Bell Telephone Laboratories in New Jersey, were studying the Milky Way's emission at microwave (radio) wavelengths, using the horn-shaped antenna shown in Figure 17.13. In their data they noticed a bothersome background "hiss"—a little like the background static on an AM radio station. Regardless of where and when they pointed their antenna, the hiss persisted. Never diminishing or intensifying, the weak signal was detectable at any time of the day and on any day of the year, apparently filling all of space.

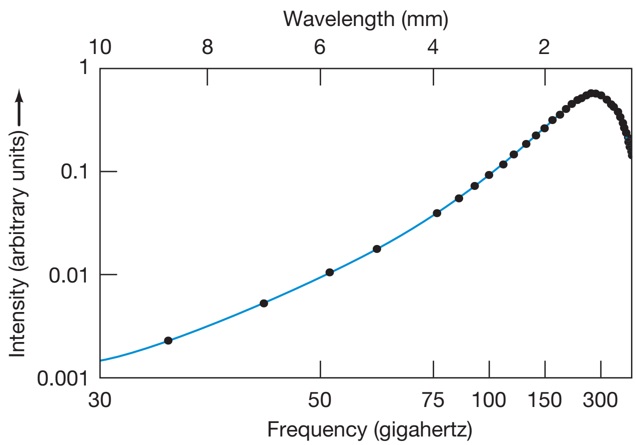
Eventually, after discussions with colleagues at Bell Labs and theorists at nearby Princeton University, the two experimentalists realized that the origin of the mysterious static was nothing less than the fiery creation of the universe itself. The radio hiss that Penzias and Wilson detected is now known as the **cosmic microwave background**. Their discovery won them the 1978 Nobel Prize in Physics.

In fact, theorists had predicted the existence and general properties of the microwave background well before its discovery. They reasoned that, in addition to being extremely dense, the early universe must also have been very *hot*, and so, shortly after the Big Bang, the universe must have been filled with extremely high-energy thermal radiation—gamma rays of very short wavelength. As illustrated in Figure 17.14, this intensely hot primordial radiation has been redshifted by the expansion of the universe from gamma rays, through optical and infrared wavelengths, all the way into the radio (microwave) range of the electromagnetic spectrum. ∞ *(Sec. 2.4)* The radiation observed today is the "fossil remnant" of the primeval fireball that existed at those very early times. The discovery of the microwave background was thus a powerful piece of evidence in support of the Big Bang theory of the universe and was instrumental in convincing many astronomers of the basic correctness of the idea.

▲ **FIGURE 17.13 Microwave Background Discoverers** This "sugarscoop" antenna was built to communicate with Earth-orbiting satellites but was used by Robert Wilson (right) and Arno Penzias to discover the 2.7-K cosmic background radiation. *(Alcatel-Lucent)*



▲ **FIGURE 17.14 Cosmic Blackbody Curves** Theoretically derived blackbody curves for the entire universe (a) 1 second after the Big Bang, (b) 100,000 years later, (c) 10 million years after that, and (d) today, approximately 14 billion years after the Big Bang.



▲ **FIGURE 17.15 Microwave Background Spectrum** The intensity of the cosmic background radiation, as measured by the *COBE* satellite, agrees well with theory. The curve is the best fit to the data, corresponding to a temperature of 2.725 K. Experimental errors in this remarkably accurate observation are smaller than the dots representing the data points.

Researchers at Princeton confirmed the existence of the microwave background and estimated its temperature at about 3 K. However, this part of the electromagnetic spectrum happens to be very difficult to observe from the ground, and it was 25 years before astronomers could demonstrate conclusively that the radiation was indeed described by a blackbody curve. ∞ *(Sec. 2.3)* In 1989 the *Cosmic Background Explorer* satellite—*COBE* for short—measured the intensity of the microwave background at wavelengths straddling the peak, from half a millimeter to about 1 cm. The results are shown in Figure 17.15. The solid line is the blackbody curve that best fits the *COBE* data. The near-perfect fit corresponds to a universal temperature of just over 2.7 K.

A striking aspect of the cosmic microwave background is its high degree of *isotropy*. When we correct for Earth's motion through space (which causes the microwave background to appear a little hotter than average in front of us and slightly cooler behind, by the Doppler effect), the intensity of the radiation is virtually constant (to about one part in 10^5) from one direction in the sky to another.

Remarkably, the cosmic microwave background contains more energy than has been emitted by all the stars and galaxies that have ever existed in the history of the universe. Stars and galaxies, though very intense sources of radiation, occupy only a small fraction of space. When their energy is averaged out over the volume of the entire cosmos, it falls short of the energy in the microwave background by at least a factor of 10. For our present purposes, then, the cosmic microwave background is the only significant form of radiation in the universe.

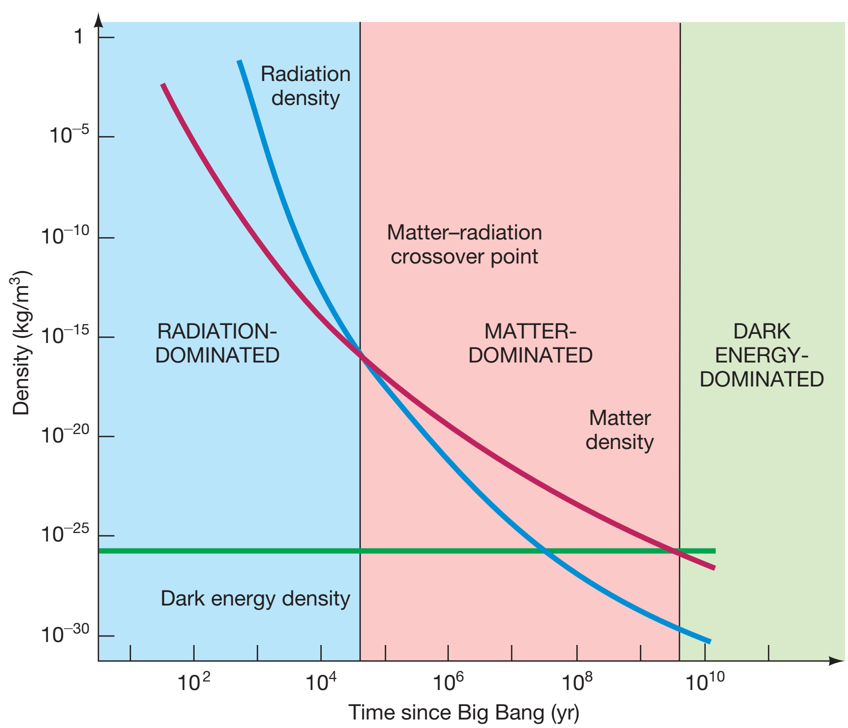
CONCEPT CHECK

When was the cosmic microwave background formed? Why is it still a blackbody curve?

Radiation in the Universe

What role does radiation play in the evolution of the universe on large scales? We can begin to address this question by expressing the energy in the microwave background as an equivalent density, calculating the number of photons in a cubic meter of space, and then converting the total energy of these photons into a mass using the relation $E = mc^2$. ∞ *(Sec. 16.6)* When we do this, we find an equivalent density for the microwave background of about 5×10^{-21} kg/m^3—much less than the current value of the cosmic density, which as we have just seen (Figure 17.10), is roughly 9×10^{-27} kg/m^3, virtually all in the form of dark energy and matter. Thus, *at the present moment*, the densities of both dark energy and matter in the universe far exceed the density of radiation.

Has this always been the case? Have dark energy and matter always dominated the cosmos? To answer this we must understand how the densities of dark energy, matter, and radiation change as the universe expands. According to current theory, dark energy is a property of space itself, and its density remains *constant* as the universe evolves. In contrast, the densities of matter and radiation both *decrease*, as the expansion dilutes the numbers of atoms and photons alike, but the radiation is further diminished in energy by the cosmological redshift, so its equivalent density falls even faster than the density of matter as the universe grows. Thus, as illustrated in Figure 17.16, even



◀ **FIGURE 17.16 Changing Dominance** As the universe expanded, the numbers of both matter particles and photons per unit volume decreased. The photons were additionally reduced in energy by the cosmological redshift. As a result, the density of radiation fell faster than the density of matter as the universe grew, and that radiation dominated matter at early times, before the crossover point. Today, dark energy dominates both matter and radiation.

though dark energy dominates today, it was *unimportant* in the early universe. Furthermore, even though the present density of radiation is much less than that of matter, there must have been a time in the past when they were equal, and before that time, radiation was the *main* constituent of the cosmos. At early times the universe was **radiation-dominated**.

17.6 Formation of Nuclei and Atoms

According to the Big Bang theory, at the very earliest times the cosmos consisted entirely of radiation. During the first minute or so of the universe's existence, temperatures were high enough that individual photons of radiation had sufficient energy to transform themselves into matter in the form of elementary particles. This period saw the creation of all the basic building blocks of matter we know today—both "normal" matter, such as protons, neutrons, and electrons, and the "exotic" particles that may compose the dark matter in galaxies and galaxy clusters. *(Sec. 14.5)* Since then, matter has evolved, clumping together into more and more complex structures forming the nuclei, atoms, planets, stars, galaxies, and large-scale structure we know today, but no *new* matter has been created. *Everything we see around us formed out of radiation as the early universe expanded and cooled.*

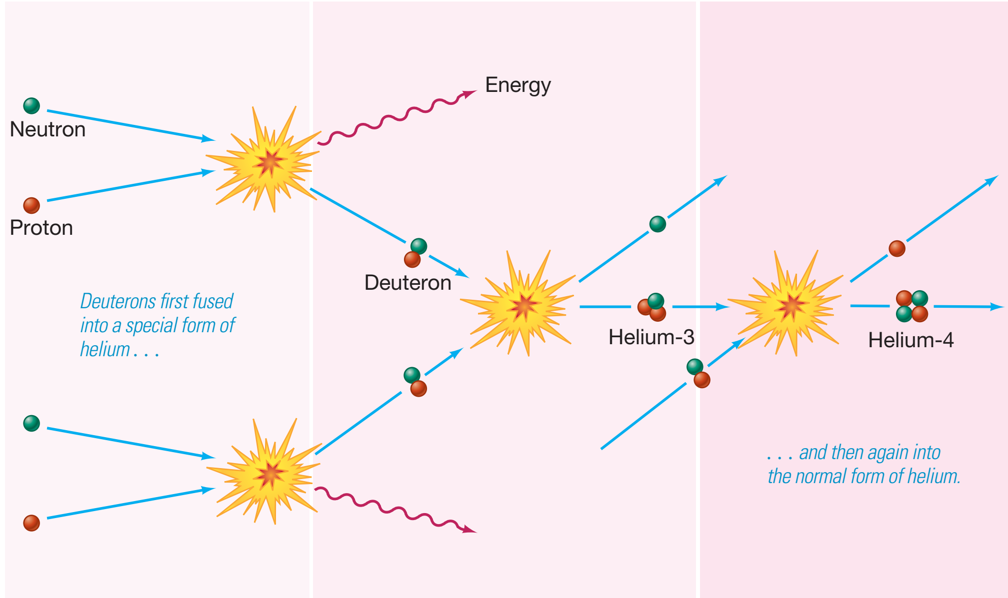
Helium Formation

As the temperature of the universe fell below about 900 million K, roughly 2 minutes after the Big Bang, conditions became favorable for protons and neutrons to fuse to form deuterium.[2] Prior to that time, deuterium nuclei were broken apart by high-energy gamma rays as quickly as they were created. Once the deuterium was at last able to survive the radiation background, other fusion reactions quickly converted it into heavier elements, especially helium-4. In just a few minutes, most of the available neutrons were consumed, leaving a universe whose "normal" matter content was primarily hydrogen and helium, with a trace of deuterium. Figure 17.17 illustrates some of the reactions responsible for helium formation. Contrast it with Figure 9.25, which depicts how helium is formed today in the cores of main-sequence stars such as the Sun. *(Sec. 9.5)* The production of elements heavier than hydrogen by nuclear fusion shortly after the Big Bang is called **primordial nucleosynthesis**.

This early burst of fusion did not last long. Conditions in the cooling, thinning universe became less and less conducive to further fusion reactions as time went by. For all practical purposes, primordial nucleosynthesis stopped at helium-4. Detailed calculations show that, by about 15 minutes after the Big Bang, the cosmic elemental abundance was set, and helium accounted for approximately one-quarter of the total mass of normal matter in the universe. The remaining 75 percent was hydrogen. It would be almost a billion years before nuclear reactions in stars would change these figures.

Astronomers find that no matter where they look, and no matter how low a star's supply of heavy elements may be, there is a minimum amount of helium—a little less than 25 percent by mass—in all stars. This is the case even in stars containing very few heavy elements, indicating that the helium already existed when those ancient stars formed. The accepted explanation is that this base level of helium is *primordial*—created during the early, hot epochs of the universe, before any stars had formed, as just described. The striking agreement between the theoretical calculation and actual observations of helium in stars is another key point in favor of the Big Bang theory.

[2]Recall from Chapter 9 that deuterium is simply a heavy form of hydrogen. Its nucleus contains one proton and one neutron. *(Sec. 9.5)*



▲ **FIGURE 17.17 Helium Formation** Some of the reaction sequences that led to the formation of helium in the early universe.

Nucleosynthesis and the Composition of the Universe

Although most deuterium was quickly burned into helium as soon as it formed, a small amount was left over when the primordial nuclear reactions ceased. Nucleosynthesis calculations indicate that the amount of deuterium remaining is a very sensitive indicator of the present-day density of matter in the universe: The *denser* the universe is today, the more matter (protons and neutrons) there was at those early times to react with the deuterium and the less deuterium was left when nucleosynthesis ended. Comparison between theoretical calculations of the production of deuterium in the early universe and the observed abundance of deuterium in stars and the interstellar medium implies a present-day density of at most 3 or 4 percent of the critical value.

But there is an important qualification. Primordial nucleosynthesis depends only on the presence of protons and neutrons in the early universe. Thus, measurements of the abundance of helium and deuterium tell us only about the density of "normal" matter—matter made up of protons and neutrons—in the cosmos. This finding has a momentous implication for the overall composition of the universe. Since the total matter density is about one-third the critical value, if the density of normal matter is only a few percent of this density, then we are forced to conclude that not only is most of the matter in the universe dark, but most of the dark matter is *not* composed of protons and neutrons (see Figure 17.10). The bulk of the matter in the universe apparently exists in the form of elusive subatomic particles whose nature we do not fully understand and whose very existence has yet to be conclusively demonstrated in laboratory experiments. ∞ *(Sec. 14.5)*

For the sake of brevity, we will adopt from here on the convention that the term *dark matter* refers only to these unknown particles and not to "stellar" dark matter, such as brown or white dwarfs, which are made of normal matter.

CONCEPT CHECK

How do we know that most of the dark matter in the universe is not of "normal" composition?

The Formation of Atoms

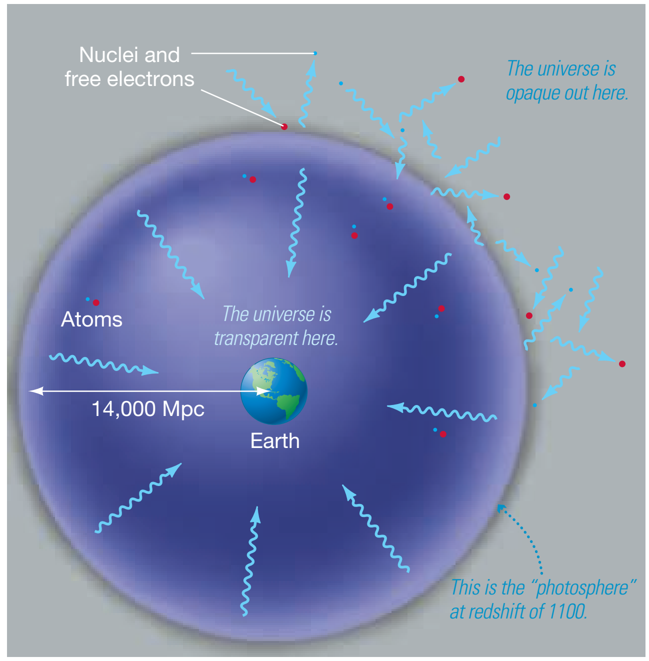
INTERACTIVE
Creation of the Cosmic Microwave Background

When the universe was tens of thousands of years old, matter (consisting of electrons, protons, helium nuclei, and dark matter) began to dominate over radiation.

The temperature at that time was several tens of thousands of kelvins—too hot for atoms of hydrogen to exist, although some helium ions may already have formed. During the next few hundred thousand years, the universe expanded by another factor of 10, the temperature dropped to a few thousand kelvins, and electrons and nuclei combined to form neutral atoms. By the time the temperature had fallen to 3000 K, the universe consisted of atoms, photons, and dark matter.

The period during which nuclei and electrons combined to form atoms is often called the epoch of **decoupling**, for it was during this period that the radiation background parted company with normal matter. At early times, when matter was ionized, the universe was filled with large numbers of free electrons that interacted frequently with electromagnetic radiation of all wavelengths. A photon could not travel far before encountering an electron and scattering off it. The universe was *opaque* to radiation. However, when the electrons combined with nuclei to form atoms of hydrogen and helium, only certain wavelengths of radiation—those corresponding to the spectral lines of those atoms—could interact with matter. ∞ *(Sec. 2.6)* Light of all other wavelengths could travel virtually forever without being absorbed. The universe became nearly *transparent*. After that time, as the universe expanded, the radiation simply cooled, eventually to become the microwave background we observe today.

The microwave photons now detected on Earth have been traveling through the universe ever since they decoupled. According to the models that best fit the observational data, their last interaction with matter (at the epoch of decoupling) occurred when the universe was about 400,000 years old and roughly 1100 times smaller (and hotter) than it is today—that is, at a redshift of 1100. As illustrated in Figure 17.18, the epoch of atom formation created a kind of "photosphere" in the universe, often referred to as the *surface of last scattering*, completely surrounding Earth at a distance of approximately 14,000 Mpc, corresponding to a redshift of 1100. ∞ *(More Precisely 15-1)* On our side of the photosphere—that is, since decoupling—the universe is transparent. On the far side—before decoupling—it was opaque. Thus, by observing the microwave background, we are probing conditions in the universe almost all the way back in time to the Big Bang itself, in much the same way as studying sunlight tells us about the surface layers of the Sun.



▲ **FIGURE 17.18 Radiation–Matter Decoupling** When atoms formed, the universe became transparent to radiation. Thus, observations of the cosmic background radiation reveal conditions in the universe around a time when the redshift was 1100 and the temperature was less than about 3000 K. For an explanation of how we can see a region of space 14,000 Mpc (46 billion light-years) away when the universe is just 14 billion years old, see *More Precisely 15-1*.

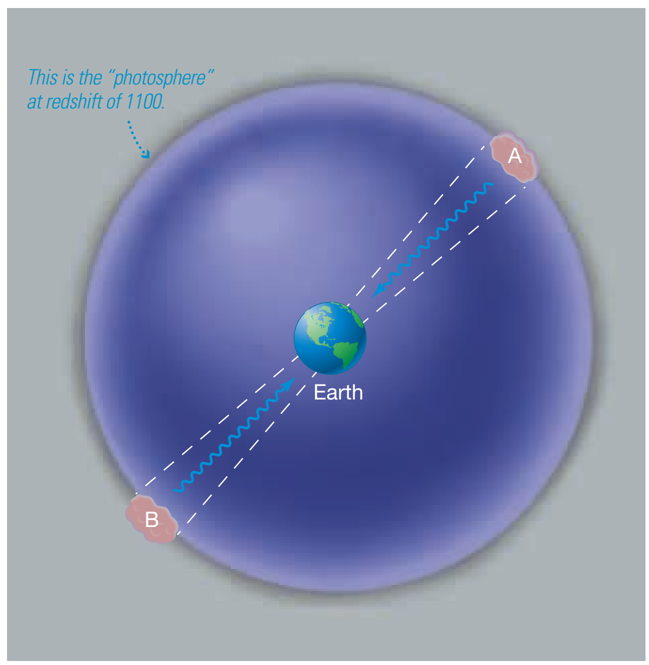
17.7 Cosmic Inflation

In the late 1970s, cosmologists were confronted with two nagging problems that had no easy explanation within the standard Big Bang model. Their resolution has caused theorists to completely rethink their views of the very early universe.

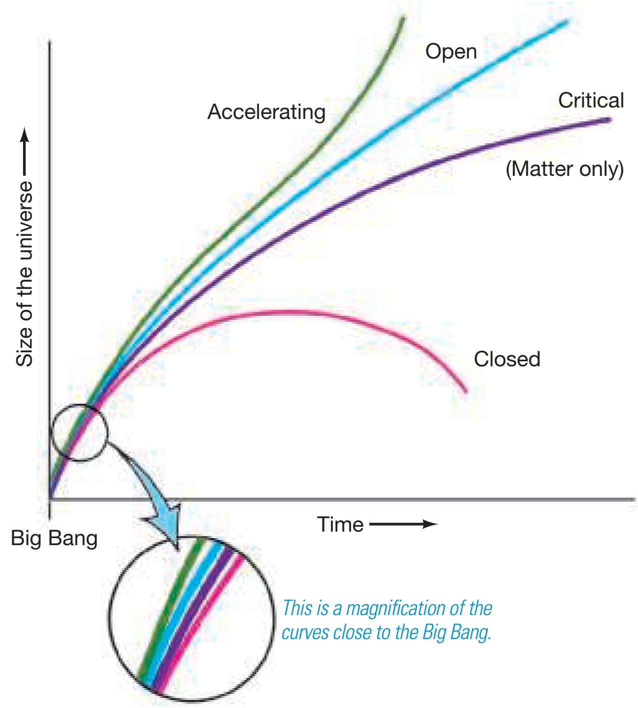
The Horizon and Flatness Problems

The first problem is known as the **horizon problem**. Imagine observing the microwave background in two opposite directions on the sky, as illustrated in Figure 17.19. As we have just seen, in doing so we are actually observing two distant regions of the universe, marked A and B on the figure, where the radiation background last interacted with matter. The fact that the background is known to be *isotropic* to high accuracy means that regions A and B must have had very similar densities and temperatures at the time the radiation we see left them.

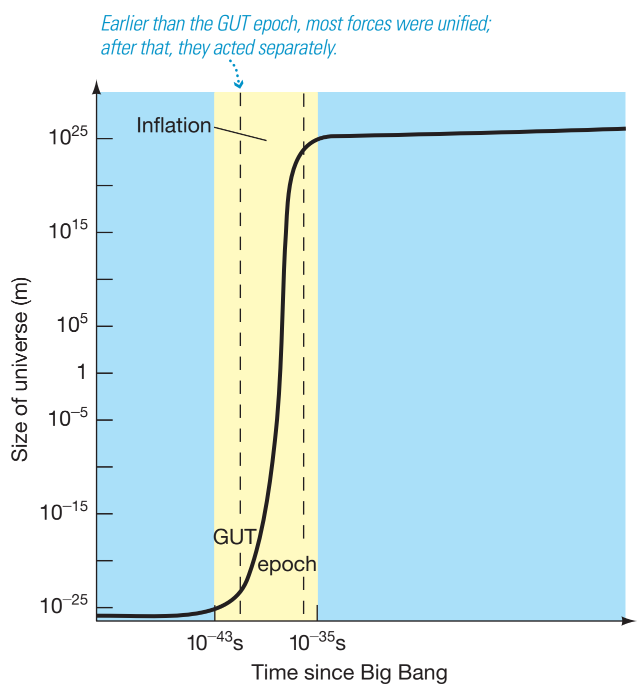
The problem is, within the Big Bang theory as just described, there is no particular reason *why* these regions should have been so similar. At the time in question, a few hundred thousand years after the Big Bang, regions A and B were separated by many megaparsecs, and no signal—sound waves, light rays, or anything else—had had time to travel from one to the other. In cosmological



▲ **FIGURE 17.19 Horizon Problem** The isotropy of the microwave background indicates that regions A and B in the universe were very similar to each other when the radiation we now observe left them, but there has not been enough time since the Big Bang for them ever to have interacted with one another. Why then should they look the same?



▲ **FIGURE 17.20 Flatness Problem** If the universe deviates even slightly from critical density, that deviation grows rapidly in time. For the universe to be as close to critical as it is today, it must have differed from the critical density in the past by only a tiny amount.



▲ **FIGURE 17.21 Cosmic Inflation** During the period of inflation, the universe expanded enormously in a very short time. Afterward, it resumed its earlier "normal" expansion rate, except that the size of the cosmos had become about 10^{50} times bigger than it was before inflation.

terminology, each region lay outside the other's *horizon*. But with no possibility of information or energy exchange between these regions, there was no way for them to "know" that they should look the same. The only alternative is that they simply started off looking alike—an assumption that cosmologists are very unwilling to make.

The second problem with the standard Big Bang model is called the **flatness problem**. Whatever the exact value of the cosmic density, it is quite close to the critical value. In terms of spacetime curvature, the universe is remarkably close to being *flat*. But again, there is no good reason why the universe should have formed with a density very close to critical. Why not a millionth or a million times that value? Furthermore, as can be seen in Figure 17.20, a universe that starts off close to, but not exactly on, the critical curve soon deviates greatly from it, so if the universe is close to critical now, it must have been *extremely* close to critical in the past. For example, even if Ω_0 were as low as 0.1 today, the departure from the critical density at the time of nucleosynthesis would have been only change: 1 part in 10^{15} (a thousand trillion).

These observations constitute "problems" because cosmologists want to be able to explain the present condition of the universe, not just accept it "as is." They would prefer to resolve the horizon and flatness problems in terms of physical processes that could have taken a universe with no special properties and caused it to evolve into the cosmos we now see. The resolution of both problems takes us back in time even earlier than nucleosynthesis or the formation of any of the elementary particles we know today—back, in fact, almost to the instant of the Big Bang itself.

The Epoch of Inflation

In the 1970s and 1980s, theoretical physicists succeeded in combining, or *unifying*, the three nongravitational forces in the universe—electromagnetism and the strong and weak forces—into a single all-encompassing "superforce." ∞ *(More Precisely 9-1)* A general prediction of the **Grand Unified Theories** (GUTs) that describe this superforce is that the three forces are unified and indistinguishable from one another *only* at enormously high energies—corresponding to temperatures in excess of 10^{28} K. At lower temperatures, the superforce splits into three, revealing its separate electromagnetic, strong, and weak characters.

In the 1980s, cosmologists discovered that Grand Unified Theories had some remarkable implications for the very early universe. Less than 10^{-34} s after the Big Bang, parts of the cosmos could have temporarily found themselves in a very odd and unstable condition in which empty space—the very fabric of the universe—acquired **vacuum energy**, in essence becoming *excited* above its normal equilibrium state. Esoteric though this sounds, these regions are of direct interest to us—if theorists are correct, we live in one!

The appearance of vacuum energy had dramatic consequences. For a short while, as illustrated in Figure 17.21, the extra energy caused the affected region to expand at an enormously accelerated rate. (The effect is similar in concept but vastly greater in magnitude than the cosmic acceleration associated with the cosmological constant, discussed in *Discovery 17-1*.) The vacuum energy density remained almost constant as the region grew, and the expansion *accelerated* with time while this out-of-equilibrium condition persisted. In fact, the size of the region doubled many times over. This period of unchecked cosmic expansion is known as the **epoch of inflation**.

Eventually, the vacuum returned to its normal "true" state and inflation stopped. Regions of normal space began to appear within the false vacuum and rapidly spread to include the entire expanding region. The whole episode lasted a mere 10^{-32} s, but during that time the patch of the universe that had become unstable swelled in size by the incredible factor of about 10^{50}. After the inflationary phase, the universe once again resumed its (relatively) leisurely expansion, but a number of important changes had occurred that would have far-reaching ramifications for the evolution of the cosmos.

The original theory of inflation was developed in the early 1980s and associated the inflationary period (as in Figure 17.21) with the end of the so-called, *GUT epoch,* as temperatures fell below 10^{28} K and the basic forces of nature became reorganized—a little like a gas liquefying or water freezing as the temperature drops. However, researchers have since realized that conditions suitable for inflation could have occurred under many different circumstances—and possibly *many times*—during the evolution of the early universe, making inflation a rather generic prediction of current theoretical models.

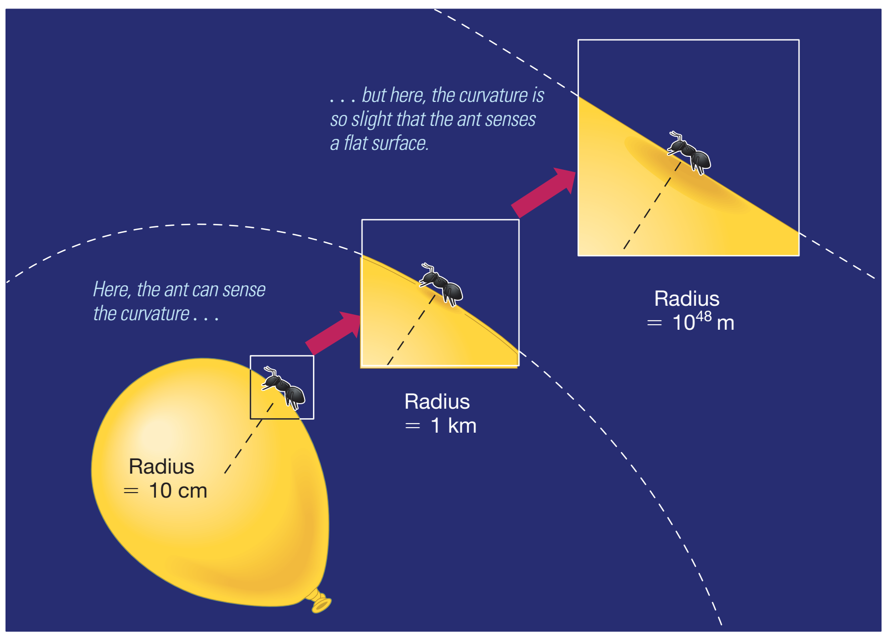
Implications for the Universe

Inflation provides a natural solution for the horizon and flatness problems. The horizon problem is solved because inflation took regions of the universe that had already had time to communicate with one another—and so had established similar physical properties—and then dragged them far apart, well out of communication range. In effect, the universe expanded much faster than the speed of light during the inflationary epoch, so what was once within the horizon now lies far beyond it. (Relativity restricts matter and energy to speeds less than the speed of light, but imposes no such limit on the universe as a whole.) Regions A and B in Figure 17.19 have been out of contact with one another since 10^{-32} s after the Big Bang, but they *were* in contact before then. Their properties are the same today because they were the same long ago, before inflation separated them.

Figure 17.22 illustrates how inflation solves the flatness problem. Imagine that you are a 1-mm-long ant sitting on the surface of an expanding balloon. When the balloon is just a few centimeters across, you can easily see that its surface is curved because its circumference is comparable to your own size. However, as the balloon expands, the curvature becomes less pronounced. When the balloon is a few kilometers across, your "ant-sized" patch of the surface looks quite flat, just as Earth's surface looks flat to us. Now imagine that the balloon expands 100 trillion trillion trillion trillion times. Your local patch of the surface would be completely indistinguishable from a perfectly flat plane. Thus, any curvature the universe may have had before inflation has been expanded so much that space is now perfectly flat on all scales we can ever hope to observe.

This resolution to the flatness problem—the universe appears close to being flat because the universe *is* in fact precisely flat, to very high accuracy—has another very important consequence. Because the universe is geometrically flat, relativity tells us the total density must be exactly equal to the critical value: $\Omega_0 = 1$ (Section 17.3). This is the key result that led us to conclude in Section 17.4 that dark energy—whatever it is—must dominate total density of the universe. Not only is most matter dark (Section 17.6), but *most of the cosmic density isn't made up of matter at all.*

Even though inflation solves the horizon and flatness problems in a quite convincing way, for nearly two decades after it was first proposed the theory was resisted by many astronomers. The main reason was that its prediction of $\Omega_0 = 1$ was at odds with the growing evidence that the density of matter in the universe was no more than 30 percent or so of the critical value. Many cosmologists had in fact considered the possibility



▲ **FIGURE 17.22 Inflation and the Flatness Problem** Inflation solves the flatness problem by enormously expanding a curved surface, here represented by the surface of a balloon. To an ant on the surface, the balloon looks virtually flat when the expansion is complete.

that a cosmological constant might provide a way to account for the remaining 70 percent of the cosmic density, but without independent corroboration, a conclusive case could not be made. That is why the supernova observations were so important—by demonstrating acceleration in the cosmic expansion rate, they established independent evidence for the effects of dark energy and in doing so reconciled inflation with the discrepant observations.

Physicists will probably never create in terrestrial laboratories conditions even remotely similar to those that existed in the universe during the inflationary epoch. Creation of a false vacuum is (safely) beyond our reach. Nevertheless, cosmic inflation seems to be a natural consequence of many Grand Unified Theories, and it explains two otherwise intractable problems within the Big Bang theory. For these reasons, despite the lack of direct evidence for the process, inflation theory has become an integral part of modern cosmology. It makes definite, testable predictions about the large-scale geometry and structure of the universe that are critically important to current theories of galaxy formation. As we will see in the next section, astronomers are now subjecting these predictions to rigorous scrutiny.

CONCEPT CHECK

Does the theory of inflation itself say anything about the composition of the universe?

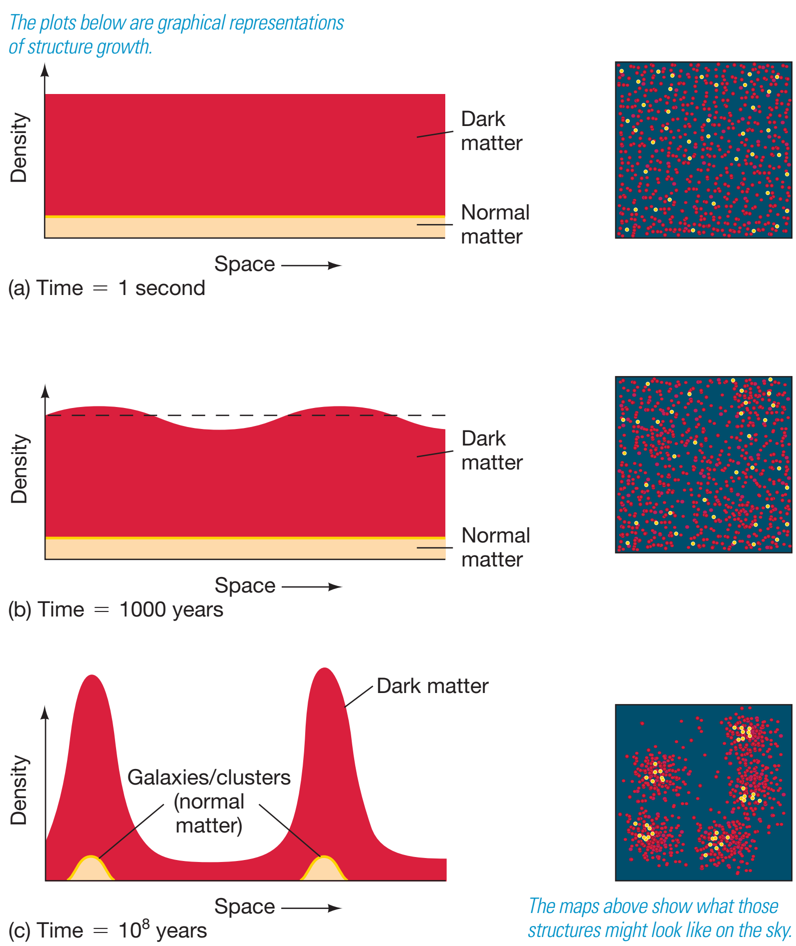
17.8 Large-Scale Structure in the Universe

ANIMATION/VIDEO
Cosmic Structure

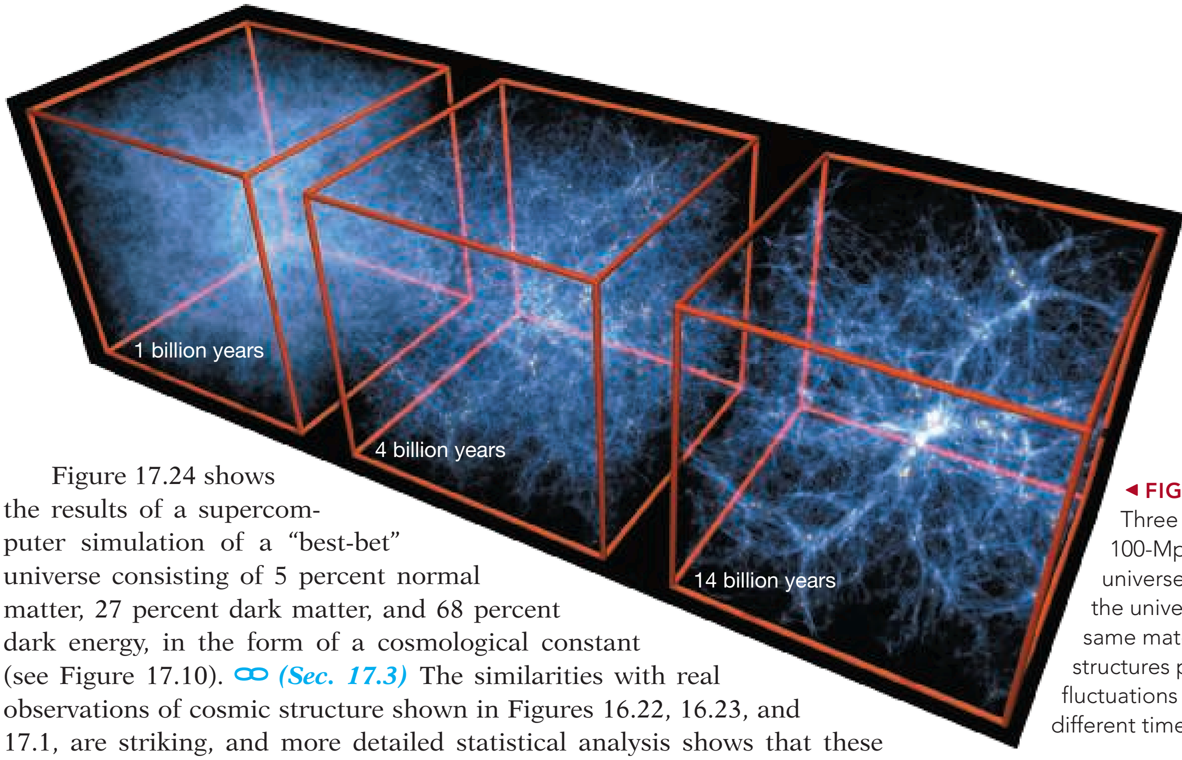
Most cosmologists think that the present large-scale structure in the universe grew from small *inhomogeneities*—slight deviations from perfectly uniform density—that existed in the early universe. Denser than average clumps of matter contracted under the influence of gravity and merged with other clumps, eventually reaching the point where stars began to form and luminous galaxies appeared. ∞ ***(Sec. 16.3)***

The intense background radiation in the early universe effectively prevented clumps of normal matter from forming or growing. Just as in a star, the pressure of the radiation stabilized the clumps against the inward pull of their own gravity. ∞ ***(Sec. 12.1)*** Instead, the first structures to appear did so in the *dark* matter that makes up the bulk of matter in the universe. While the true nature of dark matter remains uncertain, its defining property is the fact that it interacts only very weakly with both normal matter and radiation. Consequently, clumps of dark matter were unaffected by the radiation background and began to grow as soon as matter first began to dominate the cosmic density.

Thus, as illustrated in Figure 17.23, dark matter determined the overall distribution of mass in the universe and clumped to form the observed large-scale structure. Then, at later times, normal matter was drawn by gravity into the regions of highest density, eventually forming galaxies and galaxy clusters. This picture explains why so much dark matter is found outside the visible galaxies. The luminous material is strongly concentrated near the density peaks and dominates the dark matter there, but the rest of the universe is essentially devoid of normal matter. Like foam on the crest of an ocean wave, the universe we see is only a tiny fraction of the total.



◀ **FIGURE 17.23 Structure Formation** (a) The very early universe was a mixture of (mostly) dark and normal matter. (b) A few thousand years after the Big Bang, the dark matter began to clump. (c) Eventually, the dark matter formed large structures (represented here by the two high-density peaks) into which normal matter flowed, ultimately to form the galaxies seen today.



◀ **FIGURE 17.24 Structure Simulated** Three views of a (present-day) 100 × 100 × 100-Mpc cube in a simulated dark-matter universe with $\Omega_0 = 1$. The cube expands as the universe expands, so that it encloses the same material at all times. The three frames show structures progressively growing from small-density fluctuations in the early universe, displayed at three different times after the Big Bang. *(V. Springel)*

Figure 17.24 shows the results of a supercomputer simulation of a "best-bet" universe consisting of 5 percent normal matter, 27 percent dark matter, and 68 percent dark energy, in the form of a cosmological constant (see Figure 17.10). ***(Sec. 17.3)*** The similarities with real observations of cosmic structure shown in Figures 16.22, 16.23, and 17.1, are striking, and more detailed statistical analysis shows that these models in fact agree extremely well with reality. Although calculations like this cannot prove that these models are the correct description of the universe, the agreement in detail between simulations and reality strongly favor the cosmological constant/dark-matter model of the cosmos.

Dark matter does not interact directly with photons, so its growing density fluctuations did not directly affect the radiation background. However, as just described, those fluctuations were coupled to normal matter by gravity, with the result that, before decoupling, the cosmos was filled with tiny fluctuations in the density of normal matter. These density fluctuations in turn caused temperature fluctuations in the radiation field, and those features were "imprinted" in the microwave background when matter and radiation finally parted company at a redshift of 1100. Thus a key prediction of dark-matter models is that there should be tiny "ripples" in the microwave background—temperature variations of only a few parts per million from place to place on the sky.

In 1992, after almost 2 years of careful observation, the *COBE* team (Section 17.5) announced that the expected ripples had been detected. The temperature fluctuations were only 30–40 millionths of a kelvin, but they were there. The *COBE* data were limited by relatively low (roughly 7°) resolution, but combined with computer simulations such as that shown in Figure 17.24, they predicted a present-day structure that is consistent with the superclusters, voids, filaments, and Great Walls we see around us. Detailed analysis also supported the key prediction of inflation theory—that the universe is of exactly critical density and hence spatially flat. For these reasons, the *COBE* observations rank alongside the discovery of the microwave background itself in terms of their importance to the field of cosmology. The lead investigators of the *COBE* program won the 2006 Nobel Prize in physics for their groundbreaking work.

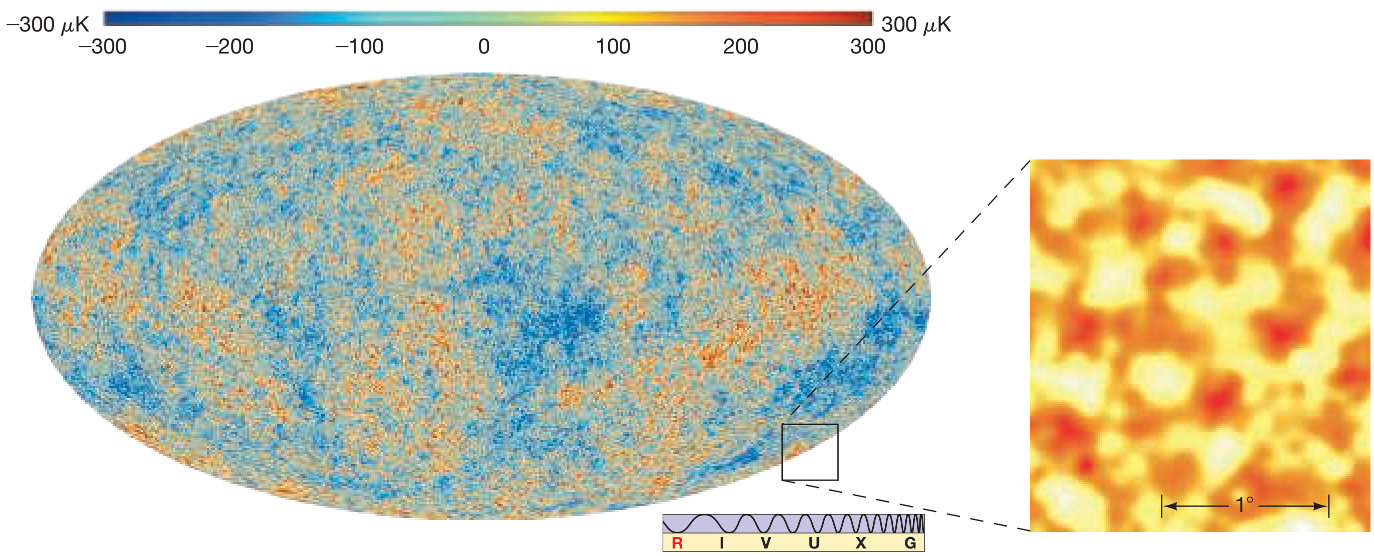
Subsequent missions have radically improved our view of the microwave background, confirming and extending the *COBE* results. NASA's *Wilkinson Microwave Anisotropy Probe* (*WMAP*) operated from 2001 until 2009. Its angular resolution was roughly 20′–30′, some 20 times finer than that of *COBE*, allowing extraordinarily detailed measurements of many cosmological parameters to be made. More recently, the European Space Agency's *Planck* mission, launched in 2009, refined

DATA POINTS

Structure in the Universe

Forty-two percent of students had difficulty describing the order in which different kinds of structure formed in the early universe. Some points to remember:

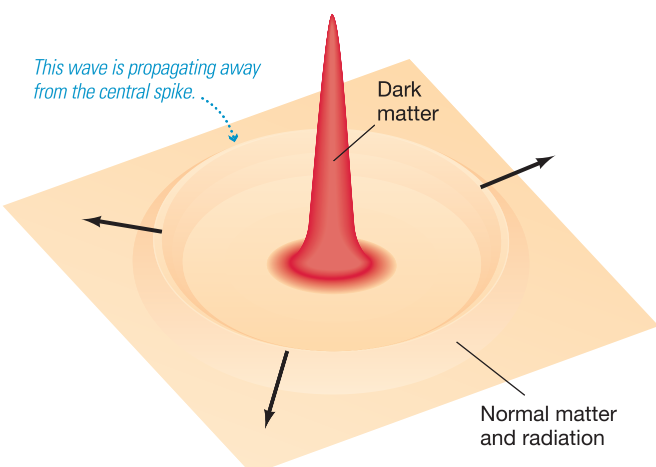
- Matter formed as the expanding universe became cool enough to allow first elementary particles (protons and neutrons), then nuclei to exist—all within the first few minutes after the Big Bang.
- The first atoms formed hundreds of thousands of years later, when the background radiation temperature dropped below a few thousand kelvins.
- Large-scale structure began to form in the dark matter component of the cosmos at very early times, not long after nuclei formed, but the radiation background prevented normal matter from clumping into stars and galaxies until long after atoms formed.
- Stars, galaxies, and quasars began to form a few hundred million years after the Big Bang, as cool gas flowed into regions of high dark matter density.



▲ **FIGURE 17.25 Early Structure** **INTERACTIVE** The entire microwave sky, as seen by the *Planck* spacecraft. The inset shows a comparably high-resolution map of a small patch of sky, obtained by the ground-based *Cosmic Background Imager* instrument at 30 GHz (1-cm wavelength). The bright blobs are slightly denser-than-average regions of the universe at an age of roughly 400,000 years; they will eventually contract to form clusters of galaxies. *(ESA; CBI)*

WMAP's observations by a further factor of 3 in resolution and 10 in sensitivity, making still more precise measurements of the microwave sky. Figure 17.25 shows an all-sky map of temperature fluctuations in the microwave background, based on *Planck* observations. The inset shows a smaller-scale (2° wide) high-resolution image returned by Cosmic Background Imager, a ground-based microwave telescope located high in the Chilean Andes. Each of the irregular high-temperature regions in these images represents a slightly denser than average clump of dark matter that will one day collapse to form a supercluster-sized clump of galaxies. According to the *Planck* data, we are seeing the universe here when it was less than 400,000 years old, yet the future development of the cosmos is already imprinted in these tiny ripples.

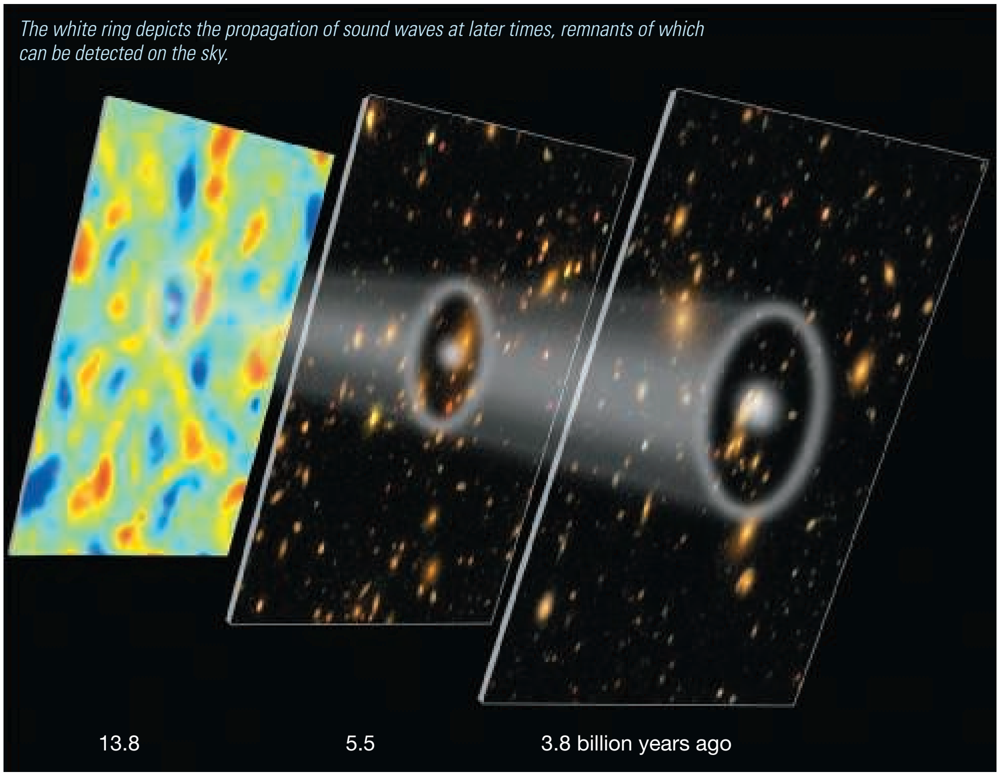
Both maps in Figure 17.25 show temperature fluctuations of a few hundred microkelvins, with a characteristic angular scale of about 1°—pretty much what your eye sees from one "blob" to the next and confirmed by more quantitative means. This scale is related to conditions in the early universe in a very important way: It corresponds to the maximum distance a sound wave can travel between the end of inflation and the time of decoupling. Sound waves were produced every time an overdense clump of dark matter began to collapse under its own gravity, eventually to form a galaxy cluster or supercluster. Normal matter and radiation were also slightly compressed by the contracting clump, but the radiation "pushed back" on the matter, causing it to expand rapidly outward in a shell, as illustrated in Figure 17.26.



▲ **FIGURE 17.26 Acoustic Oscillation** This sketch is a two-dimensional rendering of a three-dimensional wave of normal matter pushed by radiation away from a clump of dark matter in the early universe. In reality, many such sound waves would have propagated like this all over the sky wherever there were concentrations of dark matter.

The weak gravity of the dark matter clump was far too weak to prevent the shell from escaping, so it continued to expand until the epoch of decoupling, at which time the background radiation stopped interacting with normal matter and the shell stalled. The combined imprints of many overlapping shells on the microwave background sets the scale we see in Figure 17.25. Cosmologists can compute this scale for any given set of cosmological assumptions, allowing direct comparison between observations and theory. The observed fluctuations are in excellent agreement with the theoretical prediction for a universe with $\Omega_0 = 1$ and having the composition indicated in Figure 17.10.

Remarkably, these ideas also connect the microwave background to the observed distribution of galaxies at later times. Because the expanding shell just discussed itself represents a denser-than-average part of the universe, it too will tend to attract more matter, and it will eventually form galaxies of its own. The



◀ **FIGURE 17.27 Acoustic Remnants** The record of expanding sound waves in the early universe allows astronomers to retrace cosmic history. This simulation shows how the small-density variations of the early universe (left) grew to become the clusters, walls, and filaments seen in more recent times. *(Z. Rostomian/SDSS)*

result is that *every* dark matter region that forms a galaxy or galaxy cluster is expected to have associated with it a secondary shell of galaxies. This feature is imprinted on the galaxy distribution throughout the universe and at all redshifts. Figure 17.27 shows how such a ripple grows with the expansion of the universe; today, its radius would be about 150 Mpc. It forms a "standard yardstick," telling us precisely the scale of the universe at different times in the past, and represents an alternative powerful means of probing the expansion of the universe, *independent* of the supernova studies earlier in this chapter.

Of course, every density fluctuation will give rise to a similar wave, so what we actually observe is a large number of shells overlapping and mixed together. Nevertheless, astronomers can infer statistically the existence of these shells, and that has been a major goal of the *Sloan Digital Sky Survey*, which includes data from more than a million galaxies. ∞ ***(Discovery 15-1)*** The separations of those galaxies, again measured statistically, are completely consistent with the predictions of the process just described.

The first decade of the 21st century saw the basic parameters of the universe measured (even if not yet fully understood) to an accuracy only dreamed of just a few years ago. It now appears that the second decade is well on track to explore the nature of dark matter and dark energy with unprecedented precision.

MA ANIMATION/VIDEO
Ripples in the Early Universe

MA ANIMATION/VIDEO
COBE and *WMAP* View of Cosmic Microwave Background

CONCEPT CHECK

Why is dark matter important to galaxy formation? How do observations of the microwave background support this view?

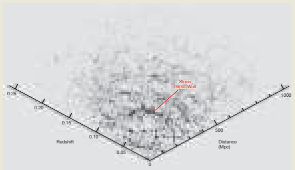
THE BIG QUESTION

What is the origin of the universe, and what will be its ultimate fate? Did it actually have an origin, or has it existed forever? Can astronomers ever hope to answer such fundamental questions? No one knows the answers, but for the first time in recorded history, human beings are using logic, rationality, and some very sophisticated (and expensive) experimental equipment to try to address them. Might we be on the cusp of answering some of the deepest queries any human has ever asked?

CHAPTER REVIEW

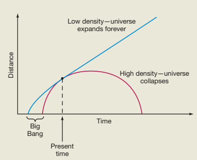
SUMMARY

LO1 On scales larger than a few hundred megaparsecs, the universe appears roughly **homogeneous** (p. 476; the same everywhere) and **isotropic** (p. 476; the same in all directions). In **cosmology** (p. 477)—the study of the universe as a whole—researchers usually assume that the universe is homogeneous and isotropic on large scales. This assumption is known as the **cosmological principle** (p. 477).

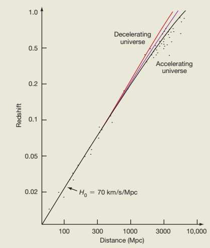


LO2 If the universe were homogeneous, isotropic, infinite, and unchanging, then the night sky would be bright because any line of sight would eventually intercept a star. The fact that the night sky is instead dark is called **Olbers's paradox** (p. 477). Its resolution is that we see only a finite part of the universe—the region within which light has had time to reach us since the universe formed. Tracing the observed motions of galaxies back in time implies that, about 14 billion years ago, the universe consisted of a single point that expanded rapidly in the **Big Bang** (p. 478). Space itself was compressed to a point at that instant—the Big Bang happened everywhere at once. The cosmological redshift occurs as a photon's wavelength is "stretched" by cosmic expansion. The extent of the observed redshift is a direct measure of the expansion of the universe since the photon was emitted.

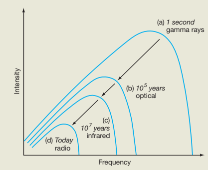
LO3 There are only two possible outcomes to the current expansion: Either the universe will expand forever, or it will recollapse to a point. The **critical density** (p. 480) is the density of matter needed for gravity to overcome the present expansion and cause the universe to collapse. The total density of the universe (including matter, radiation, and dark energy) determines the geometry of the universe on the largest scales, as described by general relativity. In a high (greater-than-critical) density universe, the curvature of space is sufficiently large that the universe "bends back" on itself and is finite in extent, somewhat like the surface of a sphere. Such a universe is said to be a **closed universe** (p. 481). A low-density **open universe** (p. 482) is infinite in extent and has a "saddle-shaped" geometry. The **critical universe** (p. 482) has a density precisely equal to the critical value and is spatially flat.



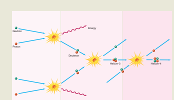
LO4 Luminous and dark matter account for only 25–30 percent of the critical cosmic density. Observations of distant supernovae suggest that the expansion of the universe may be accelerating, possibly driven by the effects of a force commonly called **dark energy** (p. 483). One candidate for this dark energy is the **cosmological constant** (p. 484), a repulsive force that may exist throughout all space. Its physical nature is unknown. Other, independent observations are consistent with the idea that the universe is flat—that is, of exactly critical density—with (mostly dark) matter making up 32 percent of the total and dark energy making up the rest. Such a universe will expand forever.



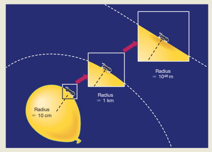
LO5 The **cosmic microwave background** (p. 487) is isotropic blackbody radiation that fills the entire universe. Its present temperature is about 3 K. Its existence is evidence that the universe expanded from a hot, dense state. As the universe has expanded, the initially high-energy radiation has been redshifted to lower and lower temperatures. At the present time, the densities of dark energy and matter in the universe both greatly exceed the equivalent mass density of radiation. The density of dark energy remains constant as the universe expands, but the matter density was much greater in the past, when the universe was smaller. However, because radiation is redshifted as the universe expands, the density of radiation was greater still. The early universe was **radiation-dominated** (p. 489).



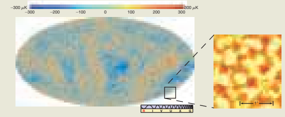
LO6 All of the hydrogen in the universe is primordial, formed from radiation as the hot early universe expanded and cooled. Most of the helium observed in the universe today is also primordial, created by fusion between protons and neutrons a few minutes after the Big Bang. This is known as **primordial nucleosynthesis** (p. 489). Other, heavier elements were formed much later, in the cores of stars. Detailed studies of this process indicate that "normal" matter can account for at most 3 percent of the critical density. By the time the universe was about 1100 times smaller than it is today, the temperature had become low enough for the first atoms to form. At that time, the (then visible) radiation background **decoupled** (p. 491) from the matter. The photons that now make up the microwave background have been traveling freely through space ever since.



LO7 According to modern **Grand Unified Theories** (p. 492), the three nongravitational forces of nature first began to display their separate characters about 10^{-34} s after the Big Bang. A



brief period of rapid cosmic expansion called the **epoch of inflation** (p. 492) ensued, during which the size of the universe increased by a factor of about 10^{50}. The **horizon problem** (p. 491) is the fact that, according to the standard (that is, noninflationary) Big Bang model, there is no good reason for widely separated parts of the universe to be as similar as they are. Inflation solves the horizon problem by taking a small homogeneous patch of the early universe and expanding it enormously. Inflation also solves the **flatness problem** (p. 492), which is the fact that there is no obvious reason why the density of the universe is so close to critical. Inflation implies that the universe is spatially flat and hence that the cosmic density is exactly critical.



LO8 The large-scale structure observed in the universe today formed when density inhomogeneities in the dark matter clumped and grew to create the "skeleton" of the structure now observed. Normal matter then flowed into the densest regions of space, eventually forming the galaxies we now see. "Ripples" in the microwave background, discovered by the *COBE* satellite, are the imprint of these early inhomogeneities on the radiation field and lend strong support to the inflationary prediction that we live in a flat, critical-density universe. Detailed observations of the microwave background, combined with studies of large-scale structure in the cosmos, provide detailed information on the basic cosmological parameters of the universe.

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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 evidence do we have that there is no structure in the universe on very large scales? How large is "very large"?
2. What is the cosmological principle?
3. What is Olbers's paradox? How is it resolved?
4. **LO2** Explain how an accurate measure of Hubble's constant can lead to an estimate of the age of the universe.
5. Why isn't it correct to say that the expansion of the universe involves galaxies flying outward into empty space?
6. Where did the Big Bang occur?
7. How does the cosmological redshift relate to the expansion of the universe?
8. What is Ω_0? What is the current best estimate of its value, and what does this imply about the geometry of the universe?
9. **LO4 POS** Why are observations of distant supernovae so important to cosmology?
10. **LO5** What is the significance of the cosmic microwave background?
11. **LO6** Why do all stars, regardless of their supply of heavy elements, seem to contain at least one-quarter helium by mass?
12. When did the universe become transparent to radiation?
13. **LO7 POS** What is cosmic inflation? How does inflation solve the horizon problem? The flatness problem?
14. **POS** What is the connection between dark matter and the formation of large-scale structure in the universe?
15. **LO8 POS** What prediction of inflation theory has since been verified by observations of the microwave background?

CONCEPTUAL SELF-TEST: TRUE OR FALSE/MULTIPLE CHOICE

1. Deep surveys of the universe indicate that the largest structures in space are about 50 Mpc in size. (T/F)
2. If the universe had an edge, that fact would violate the assumption of isotropy in the cosmological principle. (T/F)
3. Hubble's law implies that the universe will expand forever. (T/F)
4. The cosmological redshift is a direct measure of cosmic expansion. (T/F)
5. The cosmic microwave background is the highly redshifted radiation of the early Big Bang. (T/F)
6. Observations suggest that the density of the universe is made up mostly of dark matter. (T/F)
7. The microwave background radiation last interacted with matter around the time of decoupling. (T/F)
8. The theory of inflation predicts that the density of the universe is exactly equal to the critical density. (T/F)
9. Olbers's paradox is resolved by (a) the finite size of the universe; (b) the finite age of the universe; (c) light from distant galaxies being redshifted so we can't see them; (d) the fact that there is an edge to the universe.
10. The galactic distances used to measure the acceleration of the universe are determined by observations of (a) trigonometric parallax; (b) line broadening; (c) Cepheid variable stars; (d) exploding white dwarfs.
11. On the basis of our current best estimate of the present mass density of the universe, astronomers think that (a) the universe is finite in extent and will expand forever; (b) the universe is finite in extent and will eventually collapse; (c) the universe is

infinite in extent and will expand forever; (d) the universe is infinite in extent and will eventually collapse.

12. The age of the universe is estimated to be (a) less than Earth's age; (b) the same as the age of the Sun; (c) the same as the age of the Milky Way Galaxy; (d) greater than the age of the Milky Way Galaxy.

13. The horizon problem in the standard Big Bang model is solved by having the universe (a) accelerate; (b) inflate rapidly early in its existence; (c) have tiny, but significant fluctuations in temperature; (d) be geometrically flat.

14. VIS The data points in Figure 17.8 (Accelerating Universe) (a) prove that the universe is not expanding; (b) imply that the expansion is decelerating faster than expected; (c) allow a measurement of Hubble's constant; (d) indicate that the redshifts of distant galaxies are greater than would be expected if gravity alone were acting.

15. VIS According to Figure 17.16 (Changing Dominance), when the universe was 10 years old, the density of radiation was (a) much greater than that of matter; (b) much less than that of matter; (c) comparable to that of matter; (d) unknown.

PROBLEMS

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

1. ■ What is the greatest distance at which a galaxy survey sensitive to objects as faint as 20th magnitude could detect a galaxy as bright as the Milky Way (absolute magnitude –20)? ∞ *(More Precisely 10-1)*

2. ■■ If the entire universe were filled with Milky Way-like galaxies, with an average density of 0.1 per cubic megaparsec, calculate the total number of galaxies observable by the survey in the previous question if it covered the entire sky.

3. ■■ Eight galaxies are located at the corners of a cube. The present distance from each galaxy to its nearest neighbor is 10 Mpc, and the entire cube is expanding according to Hubble's law, with $H_0 = 70$ km/s/Mpc. Calculate the recession velocity (magnitude *and* direction) of one corner of the cube relative to the opposite corner.

4. ■ According to the standard Big Bang theory (neglecting any effects of cosmic acceleration), what is the *maximum* possible age of the universe if $H_0 = 50$ km/s/Mpc? 70 km/s/Mpc? 80 km/s/Mpc?

5. ■ For a Hubble constant of 70 km/s/Mpc, the critical density is 9×10^{-27} kg/m^3. (a) How much mass does this correspond to within a volume of 1 cubic astronomical unit? (b) How large a cube would be required to enclose 1 Earth mass of material?

6. ■■ The Virgo Cluster is observed to have a recessional velocity of 1200 km/s. Assuming $H_0 = 70$ km/s/Mpc and a critical-density universe, calculate the total mass contained within a sphere centered on Virgo and just enclosing the Milky Way Galaxy. What is the escape speed from the surface of this sphere? ∞ *(More Precisely 5-1)*

7. ■■ (a) What is the present peak wavelength of the cosmic microwave background? Calculate the size of the universe relative to the present size when the radiation background peaked in (b) the infrared, at 10 μm, (c) in the ultraviolet, at 100 nm, and (d) in the gamma ray, at 1 nm.

8. ■■ What were the matter density and the equivalent mass density of the cosmic radiation field when the universe was one-thousandth its present size? Assume critical density, and don't forget the cosmological redshift.

9. ■ What was the distance at the time of decoupling between the points that would eventually become the center of the Milky Way and the center of a nearby galaxy cluster, if the present distance to the cluster is 100 Mpc?

10. ■■■ The "blobs" evident in the inset to Figure 17.25 are about 20′ (arcminutes). If those blobs represent clumps of matter around the time of decoupling (redshift = 1100), and assuming Euclidean geometry, estimate the size of these clumps at the time of decoupling. ∞ *(More Precisely 15-1)*

ACTIVITIES

Collaborative

1. Make a model of a two-dimensional universe and use it to examine Hubble's law. Find a balloon that will expand into a nice, large sphere. Blow it up about halfway, and mark dots all over its surface; the dots will represent galaxies. Each group member should choose one dot as his/her home galaxy. Using a measuring tape, measure the distances to various other galaxies, numbering the dots so you will not confuse them later. Now blow the balloon up to full size and measure the distances again. Calculate the change in the distances for each galaxy; this is a measure of its velocity (change in position/change in time; the time is the same for all and is arbitrary). Plot their velocities versus their new distances as in Figure 15.16 or 17.8. Do you get a straight-line correlation, that is, a "Hubble" law? Does it matter which dot you choose as home? Demonstrate this to your class.

Individual

1. Isotropy is the extent to which things look the same in every direction. Considering buildings, geographic features, and similar objects within a few miles of your current location, is your local universe isotropic? If not, is there any scale on which isotropy applies, even approximately?
2. Write a paper on the philosophical differences between living in an open, closed, or flat universe. Are there aspects of any of these three possibilities that are hard to accept? Do you have a preference?
3. Go to your library or online and read about the *steady-state universe*, which enjoyed some measure of popularity in the 1950s and 1960s. How did it differ from the standard Big Bang model? What were its main assumptions and predictions, and why did its proponents regard it as superior to the Big Bang? Why is the steady-state model not widely accepted today—what key predictions did it make that were inconsistent with observations?

18

Life in the Universe

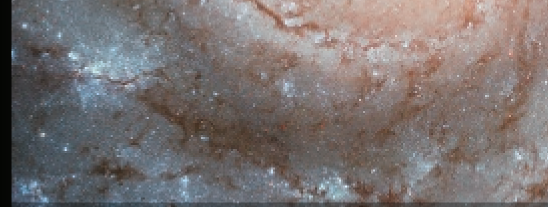
Are We Alone?

Are we unique? Is life on our planet the only example of life in the universe? If so, then what would be the implications of that momentous discovery? If not, then how and where should we look for other intelligent beings? These are difficult questions, for the subject of extraterrestrial life is one for which we have no data, but they are important questions, with profound implications for the human species. Earth is the only place in the universe where we know for certain that life exists. In this final chapter we take a look at how humans evolved on Earth and then consider whether those evolutionary steps might have happened elsewhere. Having done that, we assess the likelihood of our having Galactic neighbors and consider how we might learn about them if they exist.

THE BIG PICTURE

Earth is the only place in the universe where we know for certain that life exists. Despite the likelihood of life elsewhere in the universe, we have no clear evidence for it. None of the thousands of known extrasolar planets has yet shown any sign of life, intelligent or otherwise. Even so, astronomers keep watchful eyes on the sky, constantly aware and hopeful that evidence for extraterrestrial intelligence (ETI) might emerge at any moment.

◀ Is there intelligent life elsewhere in the universe? We saw in Chapter 4 how astronomers are amassing growing evidence of potentially Earth-like planets orbiting other stars. Perhaps, as this fanciful artist's conception suggests, Earth-like moons may orbit many giant exoplanets, providing important alternative sites for the development of extraterrestrial life. Still, despite blockbuster movies, science-fiction novels, and many claims of extraterrestrial contact, astronomers have so far found no evidence for life, intelligent or otherwise, anywhere else in the universe. Nevertheless, the search goes on.



LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Summarize the process of cosmic evolution, as it is currently understood.
- **LO2** Describe the basic ingredients of life on Earth.
- **LO3** Identify the most promising sites for life elsewhere in the solar system, and explain why they are promising.
- **LO4** Summarize the various probabilities used to estimate the number of advanced civilizations that might exist in our Galaxy.
- **LO5** Outline some techniques we might use to search for extraterrestrials and to communicate with them.

18.1 Cosmic Evolution

In our study of the universe, we have been careful to avoid any inference or conclusion that places Earth in a special place in the cosmos. This Copernican principle has been our essential guide in helping define our place in the "big picture." ∞ *(Sec. 1.1)* But when discussing the topic of life in the universe we face a problem: Ours is the only planet we know of on which life and intelligence have evolved, making it hard for any discussion of intelligent life *not* to treat humans as special cases.

Accordingly, in this final chapter we must adopt a decidedly different approach. We first describe the chain of events leading to the only technologically proficient, intelligent civilization we know—us. Then, we try to assess the likelihood of finding and communicating with intelligent life elsewhere in the cosmos.

Life in the Universe

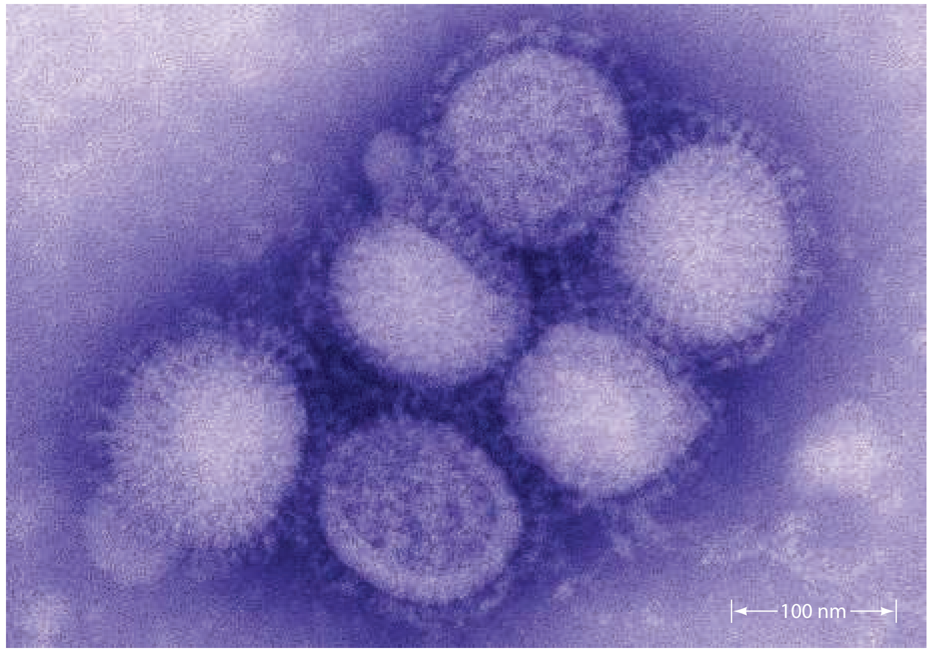
With this human-centered viewpoint clearly evident, Figure 18.1 identifies seven major phases in the history of the universe: *particulate, galactic, stellar, planetary, chemical, biological*, and *cultural* evolution. Taken together, these evolutionary stages make up the grand sweep of **cosmic evolution**—the continuous transformation of matter and energy that has led to the appearance of life and civilization on Earth. The first four phases represent, in reverse order, the contents of this book up to this point. We now expand our field of view beyond astronomy to include the other three.

From the Big Bang to the evolution of intelligence and culture, the universe has evolved from simplicity to complexity. We are the result of an incredibly complex chain of events that spanned billions of years. Were those events random, making us unique, or are they in some sense *natural*, so that a technological civilization like ours is inevitable? Put another way, are we alone in the universe, or are we just one among countless other intelligent life-forms?

Before trying to answer these important questions, we need a working definition of *life*. The distinction between the living and the nonliving is not as obvious as we might at first think. Generally speaking, scientists regard the following as characteristics of living organisms: (1) they can *react* to their

▸ **FIGURE 18.1 Arrow of Time** Some highlights of cosmic history, as it relates to the emergence of life on Earth, are noted along this arrow of time, from the beginning of the universe to the present. At the bottom of the arrow are seven "windows" outlining the major phases of cosmic evolution: evolution of primal energy into elementary particles; of atoms into galaxies and stars; of stars into heavy elements; of elements into solid rocky planets; of those elements into the molecular building blocks of life; of those molecules into life itself; and of advanced life-forms into intelligence, culture, and technological civilization. *(D. Berry)* environment and can often heal themselves when damaged; (2) they can *grow* by taking in nourishment from their surroundings; (3) they can *reproduce*, passing along some of their own characteristics to their offspring; and (4) they have the capacity for genetic change and can therefore *evolve* from generation to generation to adapt to a changing environment.

These rules are not hard and fast, and a good working definition of life is elusive. Stars, for example, react to the gravity of their neighbors, grow by accretion, generate energy, and "reproduce" by triggering the formation of new stars, but no one would suggest that they are alive. For example, a virus is inert, often crystalline in form, when isolated from living organisms, but once inside a living system, it exhibits all the properties of life, seizing control of the cell and using the cell's own genetic machinery to grow and reproduce (Figure 18.2). Most researchers think that the distinction between living and nonliving is more one of structure and complexity than a simple checklist of rules.



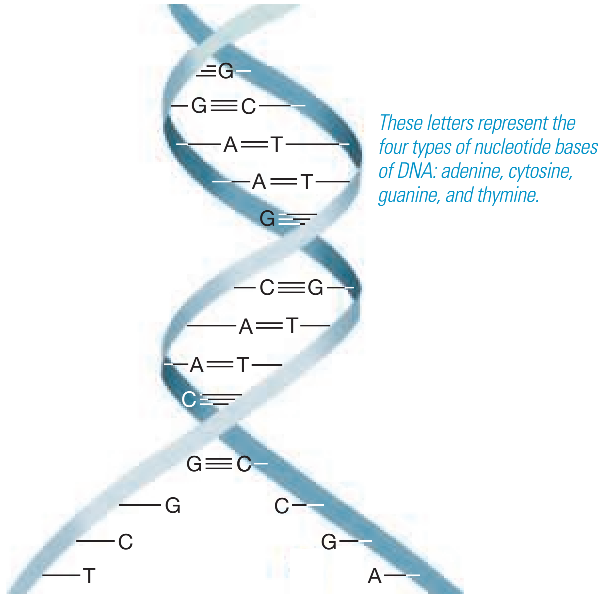
▲ **FIGURE 18.2 Virus** This electron microscope image shows the H1N1 (Swine Flu) virus that killed thousands of people worldwide in 2009. Viruses exist in the gray area between the living and the nonliving—they are lifeless when isolated from living organisms, but once inside a living system, they take on all the properties of life. A virus comes alive by transferring its genetic material into a living cell, seizing control and establishing itself as the new master of chemical activity, often with devastating results to the host organism. *(Centers for Disease Control)*

The general case in favor of extraterrestrial life is summed up in what are sometimes called the *assumptions of mediocrity*: (1) because life on Earth depends on just a few basic molecules, (2) because the elements that make up these molecules are (to a greater or lesser extent) common to all stars, and (3) if the laws of science we know apply to the entire universe (as we have supposed throughout this book), then—given sufficient time—life must have originated elsewhere in the cosmos. The opposing view maintains that intelligent life on Earth is the product of a series of extremely fortunate accidents—astronomical, geological, chemical, and biological events unlikely to have occurred anywhere else in the universe. The purpose of this chapter is to examine some of the scientific arguments for and against these viewpoints.

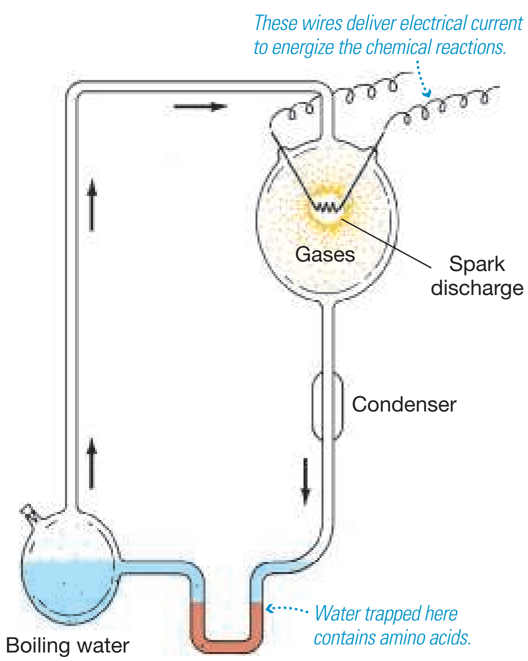
Life on Earth

What information do we have about the earliest stages of planet Earth? Unfortunately, not very much. Geological hints about the first billion years or so were largely erased by violent surface activity as volcanoes erupted and meteorites bombarded our planet; subsequent erosion by wind and water has seen to it that little evidence has survived to the present day. However, the early Earth was probably barren, with shallow lifeless seas washing upon grassless, treeless continents. Outgassing from our planet's interior through volcanoes, fissures, and geysers produced an atmosphere rich in hydrogen, nitrogen, and carbon compounds and poor in free oxygen. As Earth cooled, ammonia, methane, carbon dioxide, and water formed. The stage was set for the appearance of life.

The surface of the young Earth was a very violent place. Natural radioactivity, lightning, volcanism, solar ultraviolet radiation, and meteoritic impacts all provided large amounts of energy that eventually shaped the ammonia, methane, carbon dioxide, and water into more complex molecules known as **amino acids** and **nucleotide bases**—organic (carbon-based) molecules that are the building blocks of life as we know it. Amino acids build *proteins*, and proteins control *metabolism*, the daily utilization of food and energy by means of which organisms stay alive and carry out their vital activities. Sequences of nucleotide bases form *genes*—parts of the DNA molecule—that direct the synthesis of proteins and hence determine the characteristics of organisms (Figure 18.3). These same genes



▲ **FIGURE 18.3 DNA Molecule** The DNA (deoxyribonucleic acid) molecule contains all the genetic information needed for a living organism to reproduce and survive. Often consisting of literally tens of billions of individual atoms, its double-helix structure allows it to "unzip," exposing its internal structure to control the creation of proteins needed for a cell to function. The ordering of its constituent parts is unique to each individual organism.



▲ **FIGURE 18.4 Urey-Miller Experiment** This chemical apparatus is designed to make complex biochemical molecules by energizing a mixture of simple chemicals. Gases (ammonia, methane, carbon dioxide, water vapor) are placed in the upper bulb to simulate Earth's primordial atmosphere and then zapped by spark-discharge electrodes akin to lightening. After about a week, amino acids and other complex molecules emerge in the trap at the bottom, which simulates the primordial oceans into which heavy molecules produced in the overlying atmosphere would have fallen.

also carry an organism's hereditary characteristics from one generation to the next. In all living creatures on Earth—from bacteria to amoebas to humans—genes mastermind life, while proteins maintain it.

The first experimental demonstration that complex molecules could have evolved naturally from simpler ingredients found on the primitive Earth came in 1953. Scientists Harold Urey and Stanley Miller, using laboratory equipment somewhat similar to that shown in Figure 18.4, took a mixture of the materials thought to be present on Earth long ago—a "primordial soup" of water, methane, carbon dioxide, and ammonia—and energized it by passing an electrical discharge ("lightning") through it. After a few days, they analyzed their mixture and found that it contained many of the same amino acids found today in all living things on Earth. About a decade later, scientists succeeded in constructing nucleotide bases in a similar manner. These experiments have been repeated in many different forms, with more realistic mixtures of gases and a variety of energy sources, but always with the same basic outcomes.

None of these experiments has ever produced a living organism, and the molecules created are far less complex than the strand of DNA illustrated in Figure 18.3. Nevertheless, they demonstrate conclusively that "biological" molecules can be synthesized by strictly nonbiological means, using raw materials available on the early Earth. More advanced experiments have fashioned protein-like blobs (Figure 18.5a) that behave to some extent like true biological cells. They resist dissolution in water and tend to cluster into small droplets called *microspheres*—a little like oil globules floating on the surface of water. The walls of these laboratory-made droplets permit the inward passage of small molecules, which then combine within the droplet to produce more complex molecules too large to pass back out through the walls. As the droplets "grow," they tend to "reproduce," forming smaller droplets.

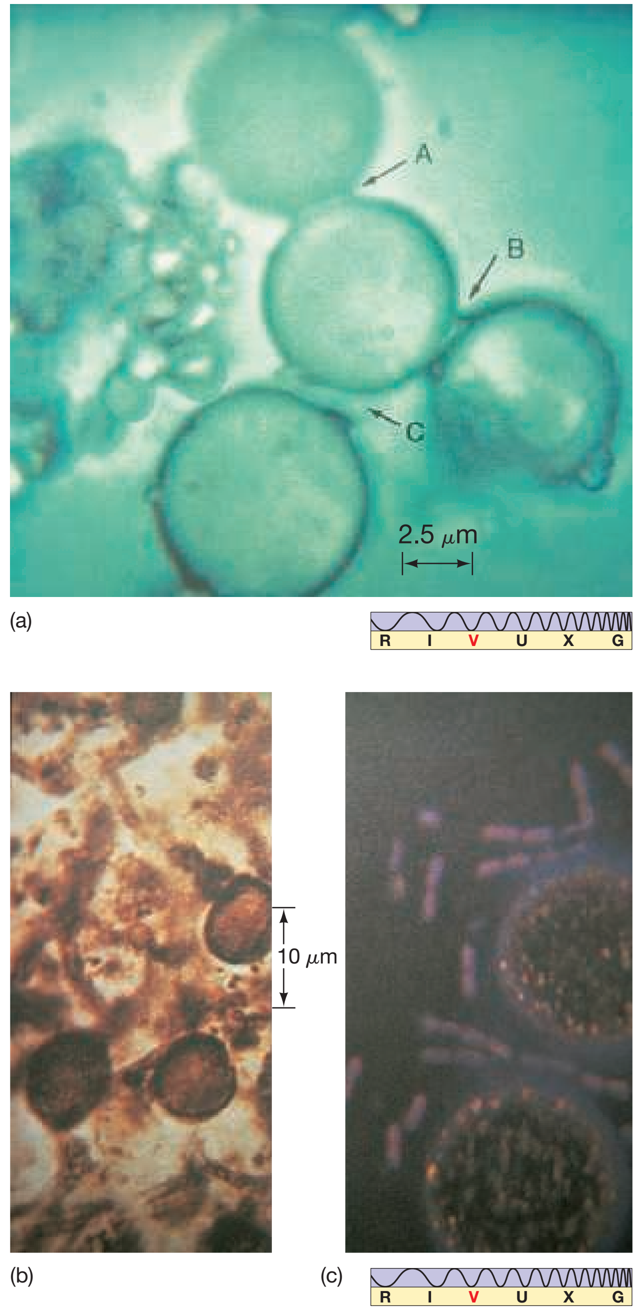
Can we consider these proteinlike microspheres to be alive? Almost certainly not. The microspheres contain many of the basic ingredients needed to form life but are not life itself. They lack the hereditary molecule DNA. However, they do have similarities to ancient cells found in the fossil record (Figure 18.5b). Thus, while no actual living cells have yet been created "from scratch," many biochemists feel that many key steps in *chemical evolution*—the chain of events leading from simple nonbiological molecules to the building blocks of life itself—have now been demonstrated.

An Interstellar Origin?

Recently, a dissenting view has emerged. Some scientists argue that there may not have been sufficient energy available to power the chemical reactions in Earth's primitive atmosphere, and there may not have been enough raw material for the reactions to occur at a significant rate in any case. Instead, they suggest, most of the organic material that combined to form the first living cells was produced in *interstellar space* and subsequently arrived on Earth in the form of interplanetary dust and meteors that did not burn up during their descent through the atmosphere.

To test this hypothesis, NASA researchers carried out their own version of the Urey-Miller experiment, exposing an icy mixture of water, methanol, ammonia, and carbon monoxide—representative of many interstellar grains—to ultraviolet radiation to simulate the energy from a nearby newborn star. As shown in Figure 18.6, when they later placed the irradiated ice in water and examined the results, they found that it had formed droplets, surrounded by membranes, containing complex organic molecules. No amino acids, proteins, or DNA were found in the mix, but the results, repeated numerous times, clearly show that even the harsh, cold vacuum of interstellar space can be a suitable medium for the formation of complex molecules and primitive cellular structures.

These three photographs, taken through a microscope, show structures on the scale of 1 micrometer, which equals 1/10,000 of a centimeter.



▶ **FIGURE 18.5 Chemical Evolution** (a) These carbon-rich, protein-like droplets contain as many as a billion amino acid molecules in a liquid sphere. The droplets can "grow," and parts of them can separate from their "parent" droplet to become new individual droplets (as at A, B, C). (b) This photograph shows primitive fossils that display concentric spheres or walls connected by smaller spheroids; they were found in sediments radioactively dated to be about 2 billion years old. (c) For comparison, modern blue-green algae are shown, on approximately the same scale. *(S. Fox/E. Barghoorn)*

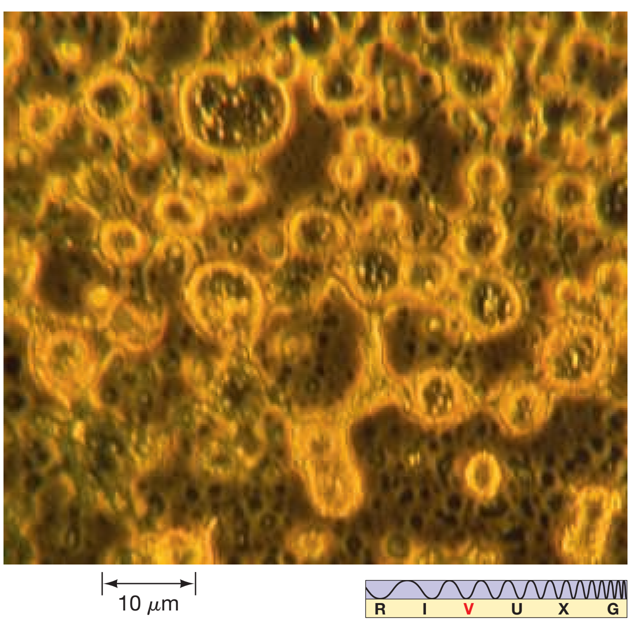
Interstellar molecular clouds are known to contain many complex molecules, and large amounts of organic material were detected on comets Halley and Hale-Bopp when they last visited the inner solar system. ∞ ***(Sec. 4.2)*** We saw earlier that many scientists think cometary impacts early in our planet's history were responsible for most of Earth's water. ∞ ***(Sec. 4.3)*** Perhaps those comets carried complex molecules, too.

In addition, a small fraction of meteorites that survive the plunge to Earth's surface (including perhaps the controversial "Martian meteorite" discussed in Chapter 6) have been shown to contain organic compounds. ∞ ***(Discovery 6-2)*** Figure 18.7 shows a particularly well-studied example, which fell near Murchison, Australia, in 1969. Located soon after crashing to the ground, this meteorite contained 12 of the amino acids normally found in living cells. Such discoveries strongly suggest that complex molecules can form in an interplanetary or interstellar environment and could have reached Earth's surface unscathed after their fiery descent.

The moderately large molecules found in meteorites and in interstellar clouds are our only evidence that chemical evolution has occurred elsewhere in the universe. However, most researchers regard this organic matter as prebiotic—matter that could eventually lead to life, but that has not yet done so. Nevertheless, the hypothesis that organic matter is constantly raining down on Earth from space in the form of interplanetary debris is quite plausible. Whether this was the *primary* means by which those molecules appeared on Earth remains unclear.

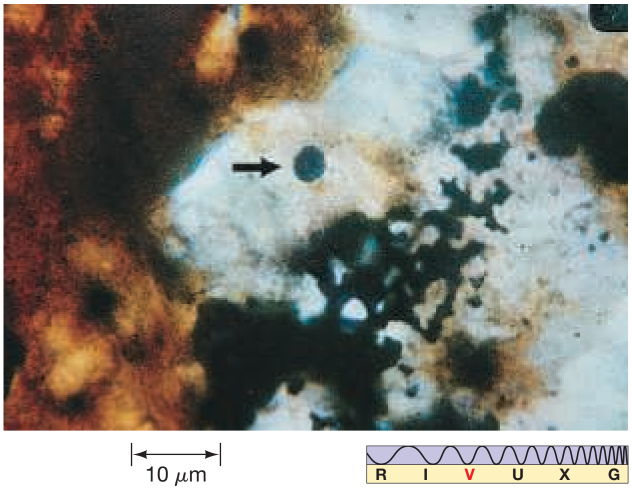
Diversity and Culture

However the basic materials appeared on Earth, we know that life *did* appear. The fossil record chronicles how life on Earth became widespread and diversified over time. The study of fossil remains shows the initial appearance about



◀ **FIGURE 18.6 Interstellar Globules** These oily, hollow droplets rich in organic molecules were made by exposing a freezing mixture of primordial matter to harsh ultraviolet radiation. When immersed in water, the larger ones display cell-like membrane structure. Although they are not alive, they bolster the idea that life on Earth could have come from space. *(NASA)*

MA® ANIMATION/VIDEO
Icy Organics in Planet-Forming Disc



▲ **FIGURE 18.7 Murchison Meteorite** The Murchison meteorite contains relatively large amounts of amino acids and other organic material, indicating that chemical evolution of some sort has occurred beyond our own planet. In this magnified view of a fragment from the meteorite, an arrow points to a microscopic sphere of organic matter. *(Harvard-Smithsonian Center for Astrophysics)*

CONCEPT CHECK

Has chemical evolution been verified in the laboratory?

3.5 billion years ago of simple one-celled organisms, such as blue-green algae. These were followed about 2 billion years ago by more complex one-celled creatures like the amoeba. Multicellular organisms did not appear until about 1 billion years ago, after which a wide variety of increasingly complex organisms flourished—among them insects, reptiles, mammals, and humans. Figure 18.8 illustrates some of the key developments in the evolution of life on our planet.

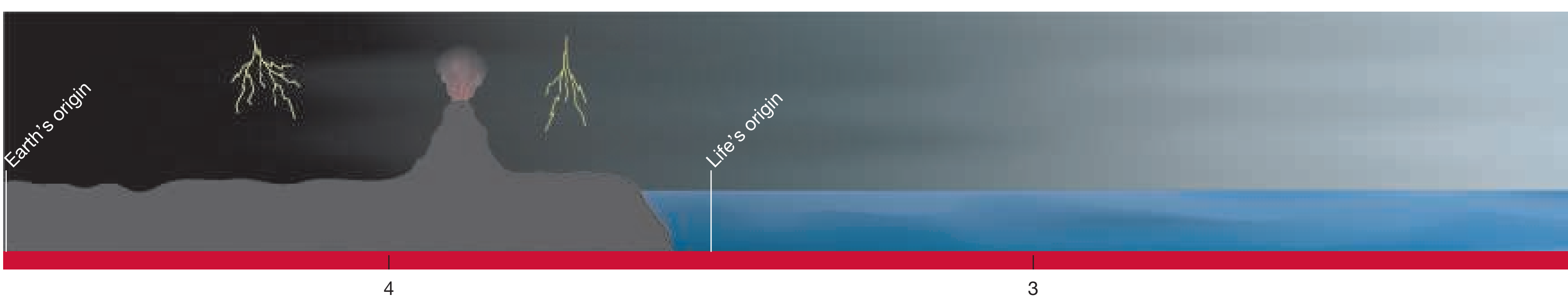
The fossil record leaves no doubt that biological organisms have changed over time—all scientists accept the reality of *biological evolution.* As conditions on Earth have shifted and Earth's surface has evolved, those organisms that could best take advantage of their new surroundings succeeded and thrived—often at the expense of those organisms that could not make the necessary adjustments and consequently became extinct.

In the opinion of many anthropologists, intelligence, like any other highly advantageous trait, is strongly favored by natural selection. The social cooperation that went with coordinated hunting efforts was an important competitive advantage that developed as brain size increased. Perhaps most important of all was the development of language. Experience and ideas, stored in the brain as memories, could be passed down from one generation to the next. A new kind of evolution had begun, namely, *cultural evolution*—the changes in the ideas and behavior of society. Our more recent ancestors created, within about 10,000 years, the entirety of human civilization.

To put all this into historical perspective, let's imagine the entire lifetime of Earth to be 46 years rather than 4.6 billion years. On this scale, we have no reliable record of the first decade of our planet's existence. Life originated at least 35 years ago, when Earth was about 10 years old. Our planet's middle age is still largely a mystery. Not until about 6 years ago did abundant life flourish throughout Earth's oceans. Life came ashore about 4 years ago, and plants and animals mastered the land only about 2 years ago. Dinosaurs reached their peak about 1 year ago, only to die suddenly about 4 months later. ∞ *(Discovery 4-1)* Humanlike apes changed into apelike humans only last week, and the latest ice ages occurred only a few days ago. *Homo sapiens*—our species—did not emerge until about 4 hours ago. Agriculture was invented within the last hour, and the Renaissance—along with all of modern science—is just 3 minutes old!

18.2 Life in the Solar System

Simple one-celled life-forms reigned supreme on Earth for most of our planet's history. It took time—a great deal of time—for life to emerge from the oceans, to evolve into simple plants, to continue to evolve into complex animals, and to develop intelligence, culture, and technology. Have those (or similar) events occurred elsewhere in the solar system? Let's try to assess what little evidence we have on the subject.



Life as We Know It

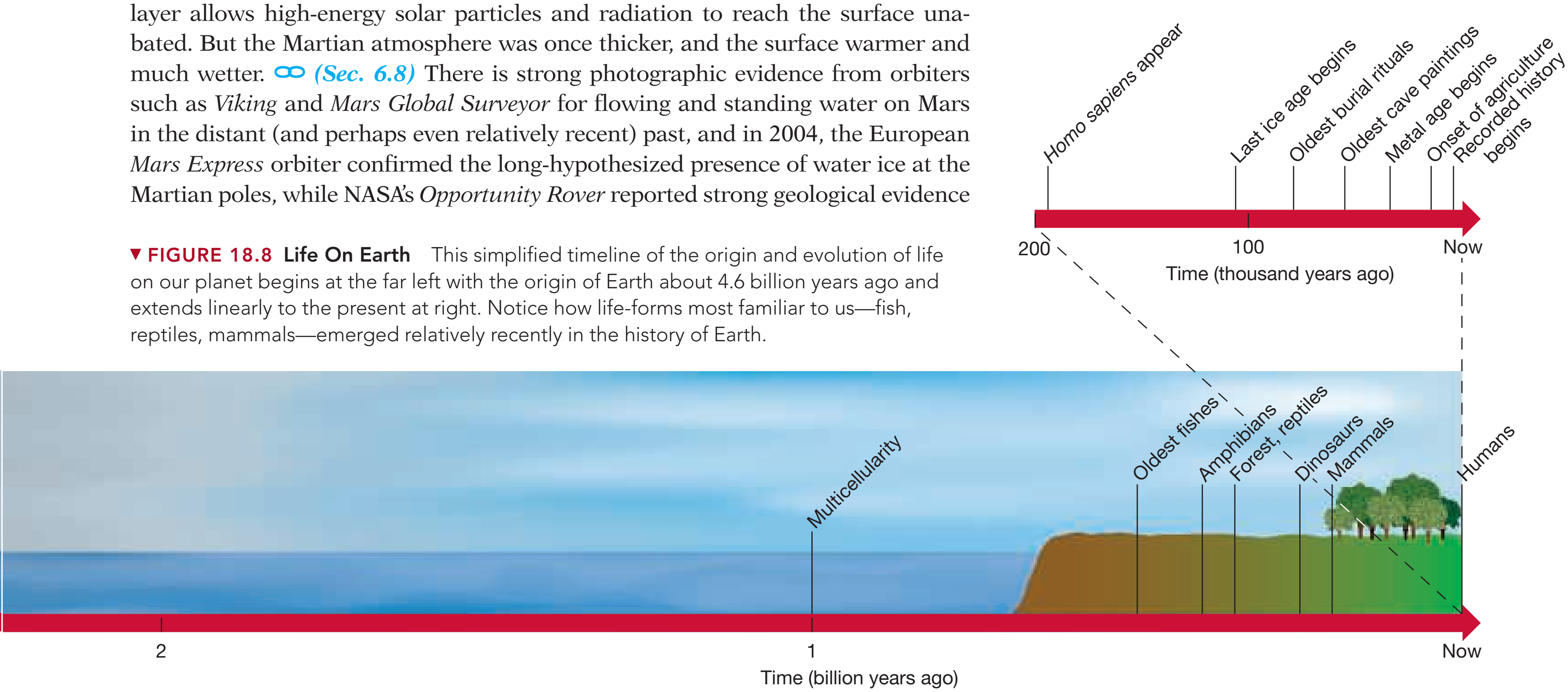
"Life as we know it" is generally taken to mean carbon-based life that originated in a liquid-water environment—in other words, life on Earth. We must always be careful in our studies not to be misled by this "Earth-centric" viewpoint—it is all too easy to attribute human or Earth-based characteristics to other life-forms—but since we have no extraterrestrial examples to guide us, at the very least this is a reasonable starting point. Thus we begin by asking, Might Earth-like life exist (or have existed) on some other body in our planetary system?

The Moon and Mercury lack liquid water, protective atmospheres, and magnetic fields, and so are subjected to fierce bombardment by solar ultraviolet radiation, the solar wind, meteoroids, and cosmic rays. Simple molecules could not survive in such hostile environments. On the other hand, Venus has far too much protective atmosphere. Its dense, dry, scorchingly hot atmospheric blanket effectively rules it out as a possible abode for life.

The jovian planets have no solid surfaces, and most of their moons (except for volcanic Io) have frozen surfaces far too cold to support Earth-like life. One possible exception is Saturn's moon Titan. With its thick atmosphere of methane, ammonia, and nitrogen gases, liquid hydrocarbon lakes, and apparent geological activity, Titan might conceivably be a place where surface life could have arisen, although the most recent results from the *Cassini-Huygens* mission suggest that the environment there would be hostile to anything remotely familiar to us. ∞ *(Sec. 8.2)*

A more promising scenario comes from the discovery that four jovian moons—Jupiter's Europa and Ganymede, and Saturn's Titan and Enceladus—may contain significant amounts of liquid water in their interiors. ∞ *(Sec. 8.1, 8.2)* This possibility has fueled speculation about the development of life within these bodies, making them prime candidates for future exploration. Europa in particular is high on the priority lists of both NASA and the European Space Agency. Again, conditions in or on these moons are far from ideal by Earthly standards, but, as we discuss below, scientists are finding more and more examples of terrestrial organisms that thrive in extreme environments once regarded as uninhabitable.

The planet most likely to harbor life (or, more likely, to have harbored it in the past) still seems to be Mars. The red planet is harsh by Earth standards—liquid water is scarce, the atmosphere is thin, and the lack of magnetism and an ozone layer allows high-energy solar particles and radiation to reach the surface unabated. But the Martian atmosphere was once thicker, and the surface warmer and much wetter. ∞ *(Sec. 6.8)* There is strong photographic evidence from orbiters such as *Viking* and *Mars Global Surveyor* for flowing and standing water on Mars in the distant (and perhaps even relatively recent) past, and in 2004, the European *Mars Express* orbiter confirmed the long-hypothesized presence of water ice at the Martian poles, while NASA's *Opportunity Rover* reported strong geological evidence

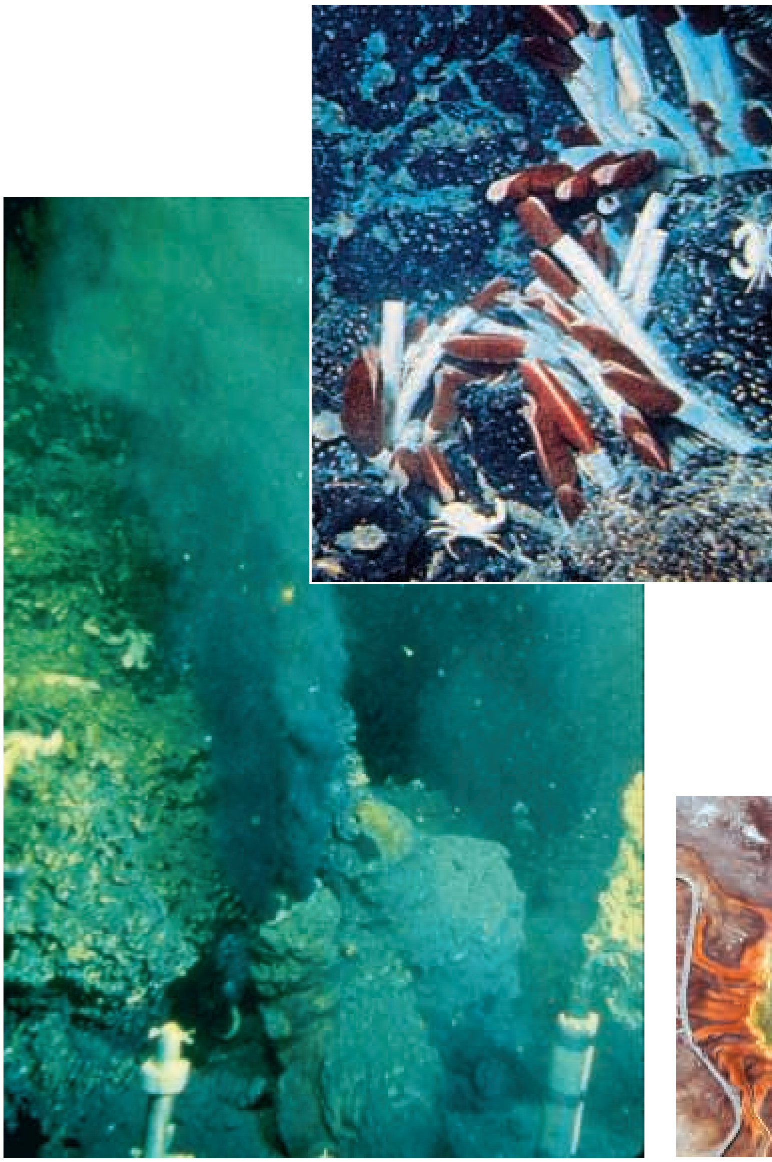


▼ **FIGURE 18.8 Life On Earth** This simplified timeline of the origin and evolution of life on our planet begins at the far left with the origin of Earth about 4.6 billion years ago and extends linearly to the present at right. Notice how life-forms most familiar to us—fish, reptiles, mammals—emerged relatively recently in the history of Earth.

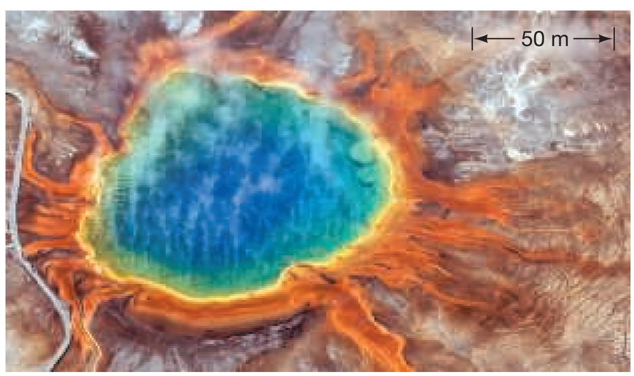
CONCEPT CHECK

Which solar system bodies (other than Earth) are the leading candidates in the search for extraterrestrial life, and why?

▼ **FIGURE 18.9 Hydrothermal Vents** (a) A two-person submarine (the *Alvin*, partly seen at bottom) took this picture of a hot spring, or "black smoker"—one of many along the mid-ocean ridge in the eastern Pacific Ocean. As hot water rich in sulfur pours out of the top of the vent's tube (near center), black clouds billow forth, providing a strange environment for many life-forms thriving near the vent. The inset shows a close-up of the vent base, where extremophilic life thrives, including as seen here giant red tube worms and huge crabs. (b) Extremophiles also thrive in inhospitable environments on Earth's surface, such as here in the Yellowstone National Park. *(WHOI)*



(a)



(b)

that the region around its landing site was once "drenched" with water for an extended period. The *Viking* landers found no evidence of life, although they landed on the safest Martian terrain, not in the most interesting regions, such as near the moist polar caps, where scientists consider life to be more likely. ∞ *(Discovery 6-2)* *Mars Pathfinder* also surveyed part of the Martian surface, again without finding any evidence of present or past life. The recent *Mars Phoenix* mission was not equipped to test for life directly, although it did confirm the presence of water in the soil near the Martian north pole. ∞ *(Sec. 6.6)* The chemical composition of the polar soil seems less Earth-like than was at first thought, but it remains to be seen how big an obstacle this poses to the chances of life on the planet.

Some scientists think that a different type of biology might be operating, or might have operated, on the Martian surface. They suggest that Martian microbes capable of digesting oxygen-rich compounds in the Martian soil could explain the *Viking* results. This speculation will be greatly strengthened if recent announcements of fossilized bacteria in meteorites originating on Mars are confirmed. ∞ *(Discovery 6-2)* The consensus among biologists and chemists today is that Mars does not house any life similar to that on Earth, but a solid verdict regarding present or past life on Mars will likely not be reached until we have thoroughly explored our intriguing neighbor.

Life in the Extreme

In considering the emergence of life under adversity, we should perhaps not be too quick to rule out an environment based solely on its extreme properties. Figure 18.9 (a) shows a very hostile environment on a deep-ocean floor, where hydrothermal vents spew forth boiling water from vertical tubes a few meters tall. The conditions are unlike anything on our planet's surface, yet life thrives in an environment rich in sulfur, poor in oxygen, and completely dark. Similar hot springs might conceivably exist on alien worlds, raising the possibility of life-forms with much greater diversity over a much wider range of conditions than those known to us on Earth.

In recent years scientists have discovered many instances of **extremophiles**—life-forms that have adapted to live in extreme environments. The superheated vents in Figure 18.9 (a) are one example, but extremophiles have also been found in frigid lakes buried millions of years ago beneath the Antarctic glaciers; in the dark, oxygen-poor and salt-rich floor of the Mediterranean Sea; in the mineral-rich acidic environment surrounding Yellowstone's volcanic Grand Prismatic Spring (Figure 18.9b); and even in the hydrogen-rich volcanic darkness far below Earth's crust. Often these organisms have evolved to create the energy they need by purely chemical means, rather than relying on sunlight. These environments may present conditions comparable to those found on Mars, Europa, or Titan, suggesting that life as we know it might be able to thrive in these hostile, alien worlds.

18.3 Intelligent Life in the Galaxy

With humans apparently the only intelligent life in the solar system, we must broaden our search for extraterrestrial intelligence to other stars, perhaps even other galaxies. At such distances, though, we have little hope of detecting life with current equipment. Instead, we must ask, How likely is it that life in any form—carbon-based, silicon-based, water-based, ammonia-based, or something we cannot even dream of—exists? Let's look at some numbers to develop statistical estimates of the probability of life elsewhere in the universe.

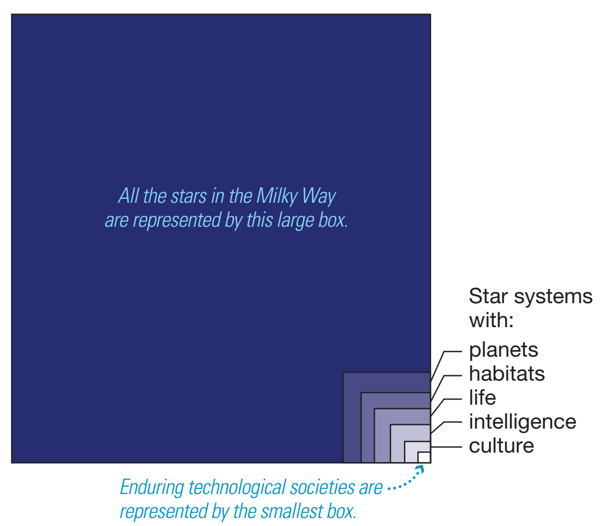
The Drake Equation

An early approach to this statistical problem is known as the **Drake equation**, after Frank Drake, the U.S. astronomer who pioneered this analysis:

number of technological, intelligent civilizations now present in the Galaxy	=	rate of star formation, averaged over the lifetime of the Galaxy	×	fraction of stars having planetary systems	×	average number of habitable planets within those planetary systems	×	fraction of those habitable planets on which life arises	×	fraction of those life-bearing planets on which intelligence evolves	×	fraction of those intelligent-life planets that develop technological society	×	average lifetime of a technologically competent civilization

Of course, several of the factors in this equation are largely a matter of opinion. We do not have nearly enough information to determine—even approximately—all of them, so the Drake equation cannot give us a hard-and-fast answer. Its real value is that it subdivides a large and very difficult question into smaller pieces that we can attempt to answer separately. Figure 18.10 illustrates how, as our requirements become more and more stringent, only a small fraction of star systems in the Milky Way Galaxy have the advanced qualities specified by the combination of factors on the right-hand side of the equation.

Let's examine the factors in the equation one by one and make some educated guesses about their values. Bear in mind, though, that if you ask two scientists for their best estimates of any given one, you will likely get two very different answers!



▲ **FIGURE 18.10 Drake Equation** Of all the star systems in our Milky Way Galaxy, progressively fewer and fewer have each of the qualities typical of a long-lasting technological society.

Rate of Star Formation

We can estimate the average number of stars forming each year in the Galaxy simply by noting that at least 100 billion stars now shine in it. Dividing this number by the roughly 10-billion-year lifetime of the Galaxy, we obtain a formation rate of 10 stars per year. This may be an overestimate because astronomers think that fewer stars are forming now than formed during earlier epochs, when more interstellar gas was available. ∞ *(Sec. 16.3)* However, we do know that stars are forming today, and our estimate does not include stars that formed in the past and have since died, so our value of 10 stars per year is probably reasonable when averaged over the lifetime of the Milky Way Galaxy.

Fraction of Stars with Planetary Systems

Many astronomers regard planet formation as a natural result of the star-formation process. If the condensation theory is correct, and if there is nothing special about our Sun, as we have argued throughout this book, we would expect many stars to have a planetary system of some sort. ∞ *(Sec. 4.3)*

As observational techniques have improved over the past two decades, these expectations have been borne out, and there is now overwhelming evidence for planets orbiting hundreds of other stars. ∞ *(Sec. 4.4)* The first planets discovered were much larger than Earth and mostly moved on eccentric or "hot" orbits, but as we saw in Chapter 4, these were the only planets that could have been detected with the instruments available at the time. As detection technology has advanced, more and more planets with masses comparable to Earth have been discovered, to the point that, since 2010, several Earth-sized planets, some of them on roughly Earth-like orbits, have been confirmed. These observations are at the very edge of current capabilities, and many astronomers expect the numbers of "Earth-like" planets to grow rapidly as new detectors come on-line.

Only about 10 percent of the nearby stars surveyed to date have been found to have planets. However, most researchers think that this is a significant underestimate of the true fraction due to observational limitations and selection effects. ∞ *(Sec. 4.4)* Thus, accepting the condensation theory and its consequences, and without being either too conservative or naively optimistic, we assign a value near 1 to this factor—that is, we think that essentially all stars have planetary systems of some sort.

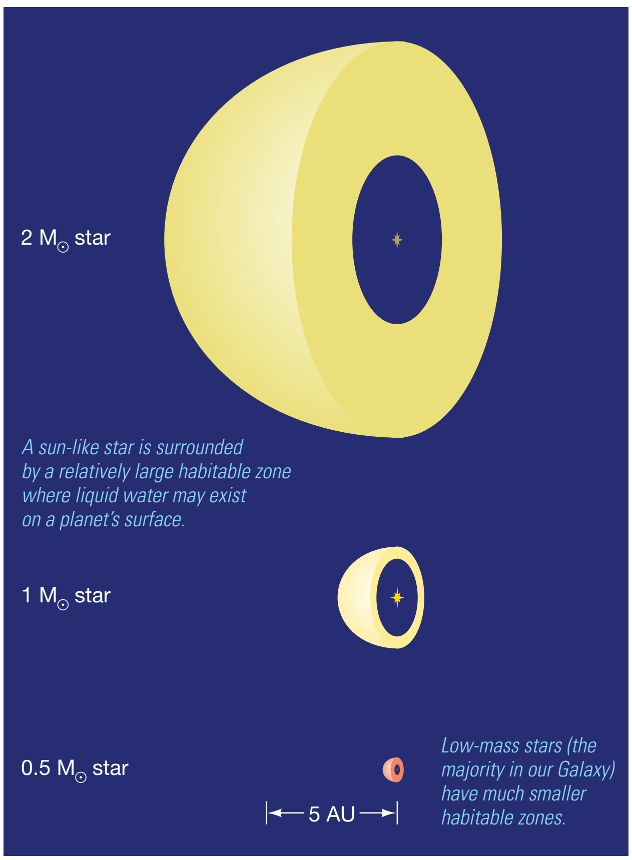
Number of Habitable Planets per Planetary System

What determines the feasibility of life on a given planet? Temperature is perhaps the single most important factor. However, the possibility of catastrophic external events, such as cometary impacts or even distant supernovae, must also be considered. ∞ *(Discovery 4-1, Sec. 12.4)*

As discussed previously (Chapter 4), the surface temperature of a planet depends on two things: the planet's distance from its parent star and the thickness of its atmosphere. ∞ *Sec. 4.4* Planets with a nearby (but not too close) parent star and some atmosphere (though not too thick) should be reasonably warm, like Earth or Mars. Objects far from the star and with no atmosphere, like Pluto, will surely be cold by our standards. And planets too close to the star and with a thick atmosphere, like Venus, will be very hot indeed.

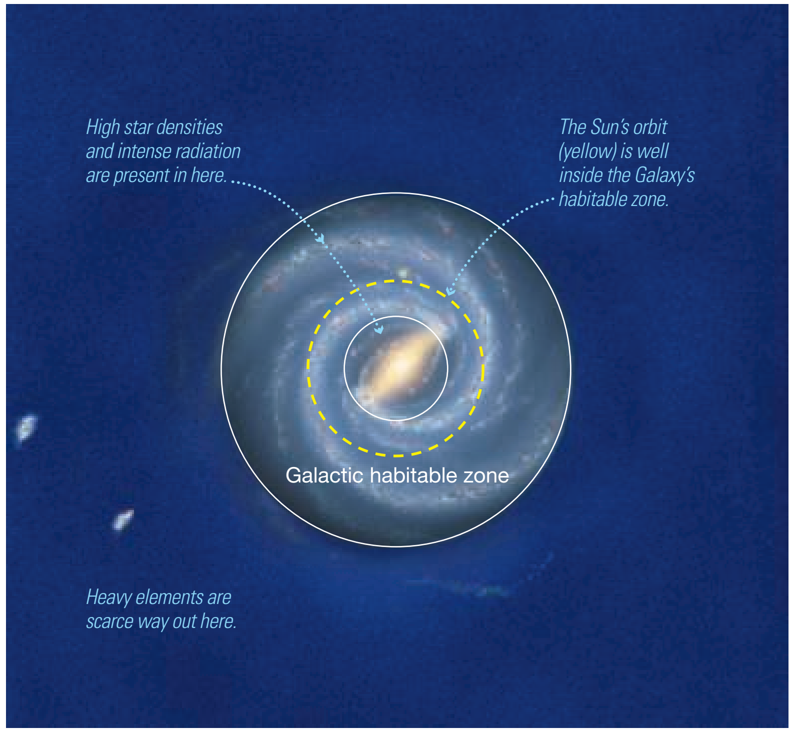
Figure 18.11 illustrates how a three-dimensional *stellar habitable zone* of "comfortable" temperatures surrounds every star. ∞ *(Sec. 4.4)* (The zones are indicated as rings in this two-dimensional figure.) The habitable zone represents the range of distances within which a planet of mass and composition similar to those of Earth would have a surface temperature between the freezing and boiling points of water. (Our Earth-based bias is plainly evident here!) The hotter the star, the larger this zone. For example, an A- or an F-type star has a rather large habitable zone. G-, K-, and M-type stars have successively smaller zones. O- and B-type stars are not considered here because they are not expected to last long enough for life to develop, even if they do have planets.

Three planets—Venus, Earth, and Mars—reside in or near the habitable zone surrounding our Sun. Venus is too hot because of its thick atmosphere and proximity to the Sun. Mars is a little too cold because its atmosphere is too thin and it is too far from the Sun. But if the orbits of Venus and Mars were swapped—not inconceivable, since chance played such a large role in the formation of the terrestrial planets—then both of these nearby planets might conceivably have evolved surface conditions resembling those on Earth. ∞ *(Secs. 4.3, 6.8)* In that case our solar system would have had three habitable planets instead of one. Perhaps just as important, proximity to a giant planet may also render the interior of a moon (such as Europa or Titan) habitable, the planet's tidal heating making up for the lack of sunlight. ∞ *(Sec. 8.1)* Sheltered by its parent planet's gravity, such a moon might be largely immune to the habitable limitations just described for planets.



▲ **FIGURE 18.11 Stellar Habitable Zones** Hot stars have bigger habitable zones than cool ones. For a G-type star like the Sun, the zone extends from about 0.8 AU to 2 AU. For a hotter F-type star, the range is 1.2 to 2.8 AU. For a cool M-type star, only Earth-like planets orbiting between about 0.02 and 0.06 AU would be habitable.

▶ **FIGURE 18.12 Galactic Habitable Zone** Some regions of the Galaxy are more conducive to life than others. Too far from the Galactic center, there may not be enough heavy elements for terrestrial planets to form or technological society to evolve. Too close, the radiative or gravitational effects of nearby stars may render life impossible. The result is a ring-shaped habitable zone, colored here in green, although its full extent is uncertain.



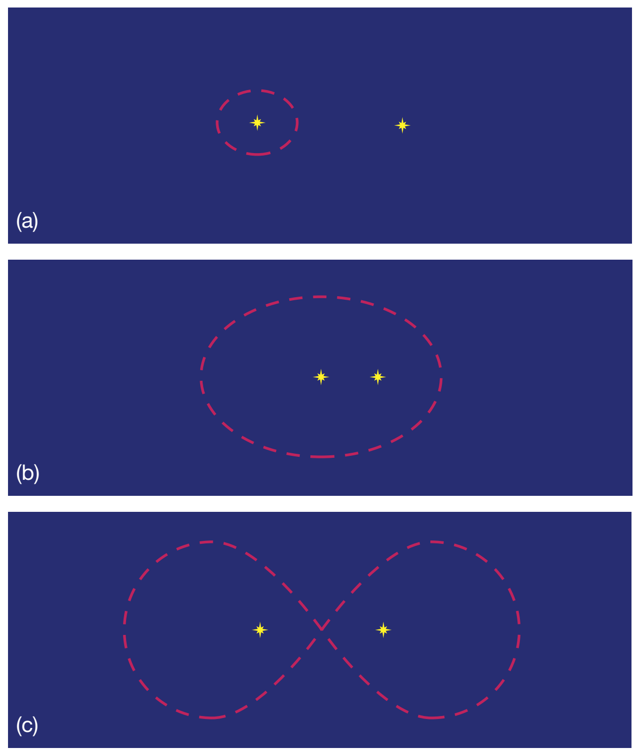
A planet moving on a "habitable" orbit may still be rendered uninhabitable by external events. Many scientists think that the outer planets in our own solar system are critical to the habitability of the inner worlds, both by stabilizing their orbits and by protecting them from cometary impacts, deflecting would-be impactors away from the inner part of the solar system. The theory presented in Chapter 4 suggests that a star with inner terrestrial planets on stable orbits would probably also need the jovian worlds to safeguard their survival. ∞ *(Sec. 4.3)* However, observations of extrasolar planets are not yet sufficiently refined to determine the fraction of stars having "outer planet" systems like our own. ∞ *(Sec. 4.4)*

Other external forces may also influence a planet's survival. Some researchers have suggested that there is a *Galactic habitable zone* for stars in general, outside of which conditions are unfavorable for life (see Figure 18.12). Far from the Galactic center, the star formation rate is low and few cycles of star formation have occurred, so there are insufficient heavy elements to form terrestrial planets or populate them with technological civilizations. ∞ *(Sec. 12.7)* Too close, and the radiation from bright stars and supernovae in the crowded inner part of the Galaxy might be detrimental to life. More important, the gravitational effects of nearby stars may send frequent showers of comets from the Oort cloud into the inner regions of a planetary system, impacting the terrestrial planets and terminating any chain of evolution that might lead to intelligent life.

Thus, to estimate the number of habitable planets per planetary system, we must first take inventory of how many stars of each type shine in the Galactic habitable zone, then calculate the sizes of their stellar habitable zones and estimate the number of planets likely to be found there. In doing so, we eliminate almost all of the stars around which planets have so far been observed, and presumably a similar fraction of stars in general. We also exclude the majority of binary star systems: Given the observed properties of binaries in our Galaxy, "habitable" planetary orbits in binary systems would be unstable in many cases, as illustrated in Figure 18.13, so there would not be time for life to develop.

The scant observational evidence currently available on Earth-like planets in habitable orbits suggests that only a few percent of the known planetary systems contain a habitable planet. ∞ *(Sec. 4.4)* However, because these planets are so close to the limits of detectability with current equipment, many astronomers think the true fraction will turn out to be significantly higher. Potentially habitable jovian moons may increase the fraction still further. However, many uncertainties remain. The inner and outer radii of the Galactic habitable zone are not known with any certainty, and the simple fact is that we still have insufficient data about most stars to make any strong statement about habitable worlds in their planetary systems.

Taking the many uncertainties into account as best we can, we assign a value of 1/10 to this factor in our equation. In other words, we think that, on average, there is 1 potentially habitable planet for every 10 planetary systems that might exist in our Galaxy. Single F-, G-, and K-type stars are the best candidates.



▲ **FIGURE 18.13 Binary Star Planets** In binary star systems, planets are restricted to only a few kinds of orbits that are gravitationally stable. (a) This orbit is stable only if the planet lies very close to its parent star, so the gravity of the other star is negligible. (b) A planet circulating at a great distance about both stars in an elliptical orbit is stable only if it lies far from both stars. (c) Another possible path interweaves between the two stars in a figure-eight pattern.

Fraction of Habitable Planets on Which Life Arises

The number of possible combinations of atoms is incredibly large. If the chemical reactions that led to the complex molecules that make up living organisms occurred completely at random, then it is extremely unlikely that those molecules could have formed at all. In that case, life is extraordinarily rare, this factor is close to 0, and we are probably alone in the Galaxy, perhaps even in the entire universe.

However, laboratory experiments (like the Urey-Miller experiment described earlier) seem to suggest that certain chemical combinations are strongly favored over others—that is, the reactions are not random. Of the billions upon billions of basic organic groupings that could possibly occur on Earth from the random combination of all sorts of simple atoms and molecules, only about 1500 actually do occur. Furthermore, these 1500 organic groups of terrestrial biology are made from only about 50 simple "building blocks" (including the amino acids and nucleotide bases mentioned earlier). This suggests that molecules critical to life may not be assembled by pure chance. Apparently, additional factors are at work at the microscopic level. If a relatively small number of chemical "evolutionary tracks" is likely to exist, then the formation of complex molecules—and hence, we assume, life—becomes much more likely, given sufficient time.

To assign a very low value to this factor in the equation is to say that life arises randomly and rarely. Assigning a value close to 1 implies that we think life is inevitable given the proper ingredients, a suitable environment, and a long enough period of time. No easy experiment can distinguish between these extreme alternatives, and there is little or no middle ground. To many researchers, the discovery of life—past or present—on Mars, Europa, Titan, or any other object in our solar system would convert the appearance of life from an unlikely miracle to a virtual certainty throughout the Galaxy. In the absence of any objective evidence, we will simply take the optimistic view and adopt a value of 1.

Fraction of Life-Bearing Planets on Which Intelligence Arises

As with the evolution of life, the appearance of a well-developed brain is a very unlikely event if only random chance is involved. However, biological evolution through natural selection is a mechanism that generates apparently highly improbable results by singling out and refining useful characteristics. Organisms that profitably use adaptations can develop more complex behavior, and complex behavior provides organisms with the *variety* of choices needed for more advanced development.

One school of thought maintains that given enough time, intelligence is inevitable. In this view, assuming that natural selection is a universal phenomenon, at least one organism on a planet will always rise to the level of "intelligent life." If this is correct, then the fifth factor in the Drake equation equals or nearly equals 1.

Others argue that there is only one known case of intelligence, and that case is life on Earth. For 2.5 billion years—from the start of life about 3.5 billion years ago to the first appearance of multicellular organisms about 1 billion years ago—life did not advance beyond the one-celled stage. Life remained simple and dumb, but it survived. If this latter view is correct, then the fifth factor in our equation is very small, and we are faced with the depressing prospect that humans may be the smartest form of life anywhere in the Galaxy. As with the previous factor, we will be optimistic and adopt a value of 1 here.

Fraction of Planets on Which Intelligent Life Develops and Uses Technology

To evaluate the sixth factor of our equation, we need to estimate the probability that intelligent life eventually develops technological competence. Should the rise of technology be inevitable, this factor is close to 1, given long enough periods of time. If it is not inevitable—if intelligent life can somehow "avoid" developing technology (as dolphins on Earth seem to have done)—then this factor could be much less than 1. The latter possibility envisions a universe possibly teeming with civilizations, but very few among them ever becoming technologically competent. Perhaps only one managed it—ours.

Again, it is difficult to decide conclusively between these two views. We don't know how many (if any) prehistoric Earth cultures either failed to develop technology or rejected its use. We do know that tool-using societies arose independently at several places on Earth, including Mesopotamia, India, China, Egypt, Mexico, and Peru. Because so many of these ancient "technological" cultures originated *independently* at about the same time, we conclude that the chances are good that some sort of technological society will inevitably develop, given some basic intelligence and enough time. Accordingly, we take this factor to be close to 1.

Average Lifetime of a Technological Civilization

The reliability of these estimates declines markedly from the first to the last factor of the Drake equation. Our knowledge of astronomy allows us to make a reasonably good stab at the first two, but even the third is hard to evaluate, and the values adopted for the last few are more wishful thinking than science. The final factor is totally unknown. There is only one example of such a civilization that we are aware of—humans on planet Earth. Our own civilization has presently survived in its technological state for only about 100 years, and how long we will be around before a human-made catastrophe or a planetwide natural disaster ends it all is impossible to tell. ∞ *(Discovery 4-1)*

One thing is certain: If the correct value for *any one factor* in the equation is very small—and we have just seen at least two for which this could well be the case, optimistic choices notwithstanding—then few technological civilizations now exist in the Galaxy. If the pessimistic view of the development of life or of intelligence is correct, then we are unique, and that is the end of our story. However, if both life and intelligence are inevitable consequences of chemical and biological evolution, as many scientists think, and if intelligent life always becomes technological, then we can plug the higher, more optimistic values into the Drake equation. In that case, combining our estimates for the other six factors (and noting that, conveniently, $10 \times 1 \times 1/10 \times 1 \times 1 \times 1 = 1$), we can say

$$\begin{array}{r} \text{number of technological} \\ \text{intelligent civilizations} \\ \text{now present in the Milky} \\ \text{Way Galaxy} \end{array} = \begin{array}{l} \text{average lifetime of a} \\ \text{technologically} \\ \text{competent civilization,} \\ \text{in years.} \end{array}$$

Thus, if advanced civilizations typically survive for 1000 years, there should be 1000 of them currently in existence scattered throughout the Galaxy. If they survive for a million years, on average, we would expect there to be a million of them in the Galaxy, and so on.

Note that even setting aside language and cultural issues, the sheer size of the Galaxy presents a significant hurdle to communication between technological civilizations. The minimum requirement for a two-way conversation is that we can send a signal and receive a reply in a time shorter than our own lifetime. If the lifetime is short, then civilizations are literally few and far between—small in number, according to the Drake equation, and scattered over the vastness of the Milky Way—and the distances between them (in light-years) are much greater than their lifetimes (in years). In that case, two-way communication, even at the speed of light, will be impossible. However, as the lifetime increases, the distances get smaller as the Galaxy becomes more crowded, and the prospects improve.

Taking into account the size, shape, and distribution of stars in the Galactic disk (why do we exclude the halo?) and under the assumptions made above, we find that unless the life expectancy of a civilization is *at least* a few thousand years, it is unlikely to have time to communicate with even its nearest neighbor.

PROCESS OF SCIENCE CHECK

If most of the factors are largely a matter of opinion, how does the Drake equation assist astronomers in refining their search for extraterrestrial life?

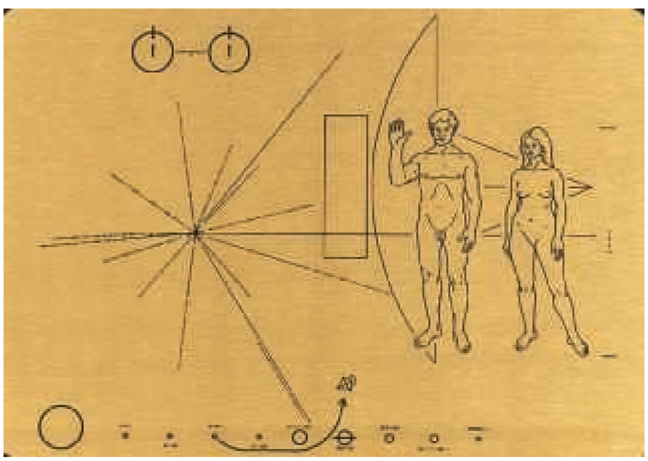
18.4 The Search for Extraterrestrial Intelligence

Let's continue our optimistic assessment of the prospects for life and assume that civilizations enjoy a long stay on their parent planet once their initial technological "teething problems" are past. In that case, they may be plentiful in the Galaxy. How might we become aware of their existence?

Meeting Our Neighbors

Let's assume that the average lifetime of a technological civilization is 1 million years—only 1 percent of the reign of the dinosaurs, but 100 times longer than our civilization has survived thus far and 10,000 times longer than human society has so far been in the "technological" state. The Drake equation then tells us that there are 1 million such civilizations in the Galaxy, and we can then estimate the average distance between these civilizations to be some 30 pc, or about 100 light-years. Thus, any two-way communication with our neighbors will take at least 200 years (100 years for the message to reach the planet and another 100 years for the reply to travel back to us)—a long time by human standards, but comfortably less than the lifetime of the civilization.

Might we hope to visit our neighbors by developing the capability of traveling far outside our solar system? This may never be a practical possibility. At a speed of 50 km/s, the speed of the current fastest space probes, the round-trip to even the nearest Sun-like star, Alpha Centauri, would take about 50,000 years. The journey to the nearest technological neighbor (assuming a distance of 100 pc) and back would take 1 million years—the entire lifetime of our civilization! Interstellar travel at these speeds is clearly not feasible. Speeding up our ships to near the speed of light would reduce the travel time, but this is far beyond our present technology.

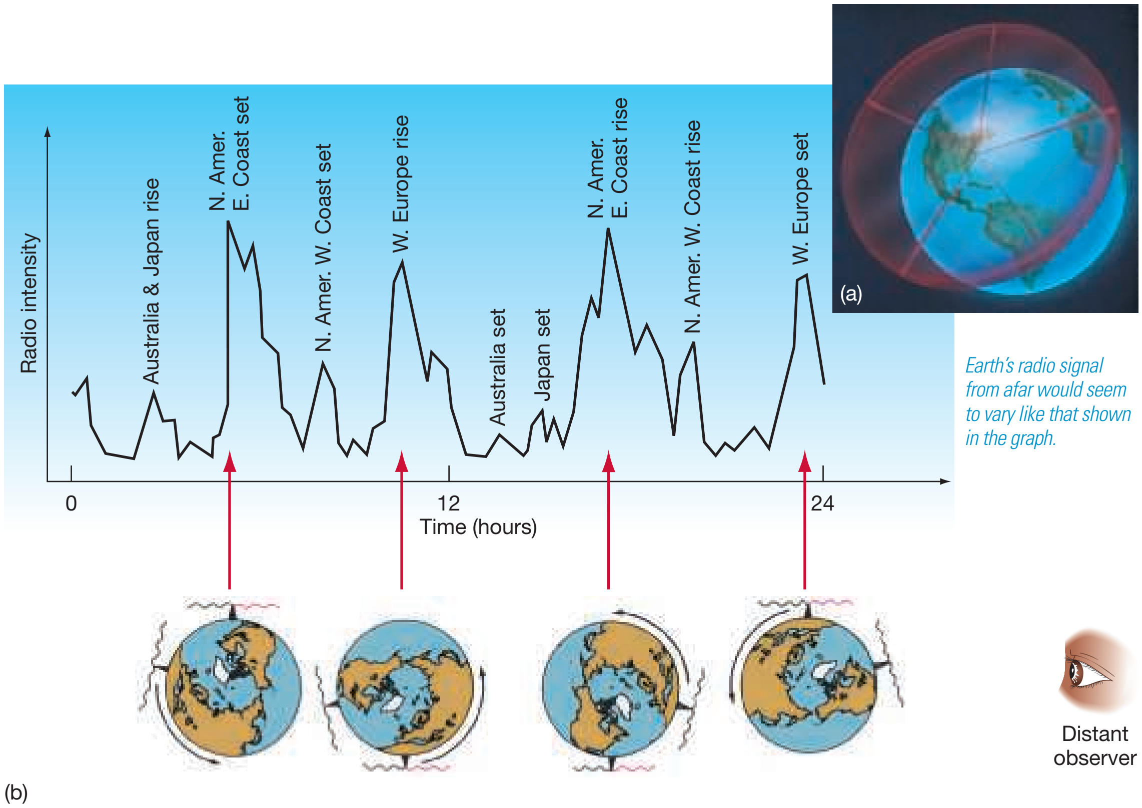


▲ **FIGURE 18.14** ***Pioneer 10* Plaque** This replica of a plaque mounted on board the *Pioneer 10* spacecraft shows a scale drawing of the craft, a man, and a woman; a diagram of the hydrogen atom undergoing a change in energy (top left); a starburst pattern representing various pulsars and the frequencies of their radio waves that can be used to estimate when the craft was launched (middle left); and a depiction of the solar system, showing that the spacecraft departed the third planet from the Sun and passed the fifth planet on its way into outer space (bottom). *(NASA)*

Actually, our civilization has already launched some interstellar probes, although they have no specific stellar destination. Figure 18.14 is a reproduction of a plaque mounted on board the *Pioneer 10* spacecraft launched in the mid-1970s and now well beyond the orbit of Pluto, on its way out of the solar system. Similar information was also included aboard the *Voyager* probes launched in 1978. While these spacecraft would be incapable of reporting back to Earth the news that they had encountered an alien culture, scientists hope that the civilization on the other end would be able to unravel most of its contents using the universal language of mathematics. The caption to Figure 18.14 notes how the aliens might discover from where and when the *Pioneer* and *Voyager* probes were launched.

Radio Searches

A cheaper and much more practical alternative is to try to make contact with extraterrestrials using electromagnetic radiation, the fastest known means of



◀ **FIGURE 18.15 Earth's Radio Leakage** Radio radiation leaks from Earth into space because of the daily activities of our technological civilization. (a) Most radio and television transmitters broadcast their energy parallel to Earth's surface, sending a great "sheet" of electromagnetic radiation into interstellar space. (b) Because the great majority of transmitters are clustered in the eastern United States and western Europe, a distant observer would detect blasts of radiation from Earth as our planet rotates each day.

transferring information from one place to another. Because light and other short-wavelength radiation are heavily scattered while moving through dusty interstellar space, long-wavelength radio radiation seems to be the best choice. ∞ *(Sec. 2.3)* We do not attempt to broadcast to all nearby candidate stars, however—that would be far too expensive and extremely inefficient. Instead, radio telescopes on Earth listen *passively* for radio signals emitted by other civilizations.

In what direction should we aim our radio telescopes? The answer to this question at least is fairly easy. On the basis of our earlier reasoning, we should target all F-, G-, and K-type stars in our vicinity. But are extraterrestrials broadcasting radio signals? If they are not, this search technique will obviously fail. If they are, how do we distinguish their artificially generated radio signals from signals emitted naturally by interstellar gas clouds? This depends on whether the signals are produced deliberately or are simply "waste radiation" escaping from a planet.

Consider first how "waste" radio wavelengths originating on Earth would look to extraterrestrials. Figure 18.15 shows the pattern of radio signals we broadcast into space. From the viewpoint of a distant observer, the spinning Earth emits a bright flash of radio radiation every few hours as the most technological regions of our planet rise or set. In fact, Earth is now a more intense radio emitter than the Sun. Our radio and television transmissions race out into space and have been doing so since the invention of these technologies nearly seven decades ago. Another civilization as advanced as ours might have constructed devices capable of detecting this radiation. If any sufficiently advanced (and sufficiently interested) civilization resides within about 70 light-years (20 pc) of Earth, then we have already announced our presence to them.

Of course, it may very well be that, having discovered cable and fiber-optics technology, most civilizations' indiscriminate transmissions cease after a few decades. In that case, radio silence becomes the hallmark of intelligence, and we must find an alternative means of locating our neighbors.

DATA POINTS

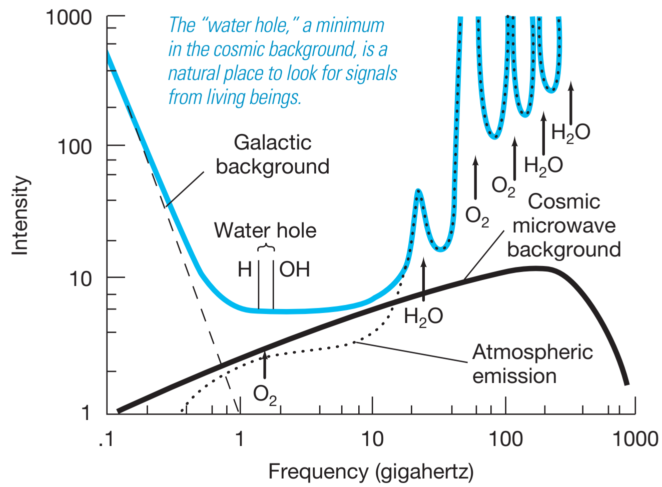
Searching for Extraterrestrial Life

Nearly 60 percent of students had difficulty describing how an electromagnetic signal might suggest extraterrestrial life. Some points to remember:

- The presence of large amounts of nitrogen and oxygen in a planet's atmosphere might suggest the presence of Earth-like life.
- Many natural cosmic sources produce steady or regularly varying electromagnetic emission.
- A regularly modulated complex signal might indicate leakage of radio or other communications from a planet's surface.
- A repeating complex signal might indicate a deliberate attempt at communication, particularly if it were transmitted in the electromagnetic "water hole," where natural background emission is minimized.

CONCEPT CHECK

What assumptions go into the identification of the water hole as a likely place to search for extraterrestrial signals?



▲ **FIGURE 18.16 Water Hole** The "water hole" is bounded by the natural emission of the hydrogen (H) atom at 21-cm wavelength and the hydroxyl (OH) molecule at 18-cm wavelength. *Sec. 11.3* The topmost solid (blue) curve sums the natural emissions of our Galaxy (dashed line) and Earth's atmosphere (dotted line). This sum is minimized near the water hole frequencies, and thus all intelligent civilizations might conduct their interstellar communications within this quiet "electromagnetic oasis."

The Water Hole

Now let us suppose that a civilization has decided to assist searchers by actively broadcasting its presence to the rest of the Galaxy. At what frequency should we listen for such an extraterrestrial beacon? The electromagnetic spectrum is enormous; the radio domain alone is vast. To hope to detect a signal at some unknown radio frequency is like searching for a needle in a haystack. Are some frequencies more likely than others to carry alien transmissions?

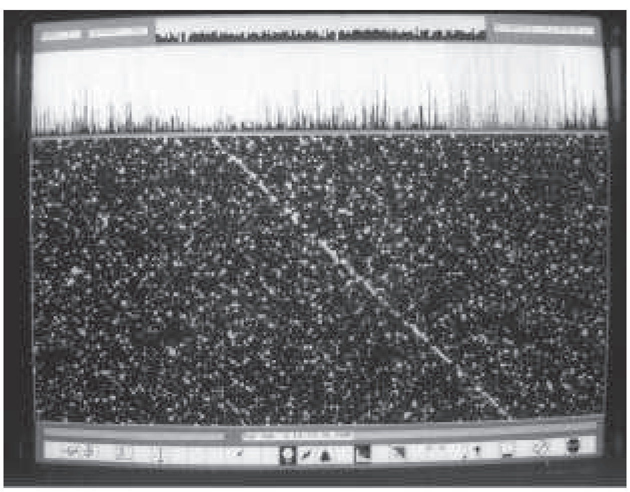
Some basic arguments suggest that civilizations might well communicate at a wavelength near 20 cm. The basic building blocks of the universe, namely, hydrogen atoms, radiate naturally at a wavelength of 21 cm. *(Sec. 11.2)* Also, one of the simplest molecules, hydroxyl (OH), radiates near 18 cm. Together, these two substances form water (H_2O). Arguing that water is likely to be the evolution medium for life anywhere and that radio radiation travels through the disk of our Galaxy with the least absorption by interstellar gas and dust, some researchers have proposed that the interval between 18 cm and 21 cm is the best wavelength range for civilizations to transmit or listen. Called the **water hole**, this radio interval might serve as an "oasis" where all advanced Galactic civilizations would gather to conduct their electromagnetic business.

This water-hole frequency interval is only a guess, of course, but its use is supported by other arguments. Figure 18.16 shows the water hole's location in the electromagnetic spectrum and plots the amount of natural emission from our Galaxy and from Earth's atmosphere. The 18- to 21-cm range lies within the quietest part of the spectrum, where the Galactic "static" from stars and interstellar clouds happens to be minimized. Furthermore, the atmospheres of typical planets are also expected to interfere least at these wavelengths. Thus, the water hole seems like a good choice for the frequency of an interstellar beacon, although we cannot be sure of this reasoning until contact is actually achieved.

A few radio searches are now in progress at frequencies in and around the water hole. One of the most sensitive and comprehensive projects in the ongoing search for extraterrestrial intelligence (known to many by its acronym SETI) is now underway with the Allen Telescope Array (Figure 18.17a). This collection of many small dishes is currently searching millions of channels simultaneously in the 1- to 3-GHz range. Figure 18.17(b) shows what a typical narrowband, 1-Hz signal—a potential "signature" of an intelligent transmission—would look like on a computer monitor. However, this observation was merely a test to detect the weak, redshifted radio signal emitted by the *Pioneer 10* robot, now receding into the outer realm of our solar system—a sign of intelligence, but one that we put there. Nothing resembling an extraterrestrial signal has yet been detected.

The space surrounding all of us could be, right now, flooded with radio signals from extraterrestrial civilizations. If only we knew the proper direction and frequency, we might be able to make one of the most startling discoveries of all time. The result would provide whole new opportunities to study the cosmic evolution of energy, matter, and life throughout the universe.

(a)



(b)

◄ **FIGURE 18.17 Project Phoenix** (a) This array of small radio dishes at the SETI Institute in California is designed to search for extraterrestrial intelligent signals. (b) A typical recording of an alien signal—here, as a test, the Doppler-shifted broadcast from the *Pioneer 10* spacecraft, now well beyond the Kuiper belt—shows a diagonal line across the computer monitor, in contrast to the random noise in the background. *(S. Shostak/SETI Institute)*

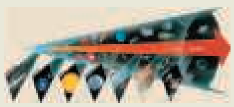
THE BIG QUESTION

Humans have long wondered if planets might orbit the innumerable stars observed in the universe. The answer, we now know, is yes. We have further wondered if there might be intelligent beings on some of those planets. Not knowing the answer, the search for extraterrestrial life continues. That is perhaps the grandest of all unsolved questions in astronomy: Do alien beings reside beyond Earth?

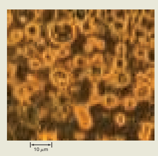
CHAPTER REVIEW

SUMMARY

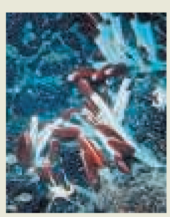
LO1 **Cosmic evolution** (p. 504) is the continuous process that has led to the appearance of galaxies, stars, planets, and life on Earth. Living organisms may be characterized by their ability to react to their environment; to grow by taking in nutrition from their surroundings; to reproduce, passing along some of their own characteristics to their offspring; and to evolve in response to a changing environment. Organisms that can best take advantage of their new surroundings succeed at the expense of those organisms that cannot make the necessary adjustments. Intelligence is strongly favored by natural selection.



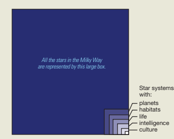
LO2 Powered by natural energy sources, reactions between simple molecules in the oceans of the primitive Earth may have led to the formation of **amino acids** (p. 505) and **nucleotide bases** (p. 505), the basic molecules of life. Amino acids build proteins, which control metabolism, while sequences of nucleotide bases make up DNA, the genetic blueprint of a living organism. Alternatively, some of these complex molecules may have been formed in interstellar space and then delivered to Earth by meteors or comets.



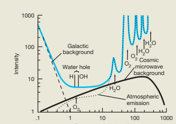
LO3 The best hope for life beyond Earth in the solar system is the planet Mars, although no direct evidence for life—current or extinct—has yet been found. Some of the icy moons of the outer planets—Jupiter's Europa and Ganymede and Saturn's Titan and Enceladus—may also be possibilities for life of some sort. Conditions on those frozen bodies are harsh by terrestrial standards, although **extremophiles** (p. 510) on Earth have been found to thrive in hostile environments in which life had previously been thought impossible.



LO4 The **Drake equation** (p. 511) provides a means of estimating the probability of other intelligent life in the Galaxy. The astronomical terms in the equation are the Galactic star-formation rate, the likelihood of planets, and the number of habitable planets. Chemical and biological terms are the probability of life appearing and the probability that it subsequently develops intelligence. Cultural and political terms are the probability that intelligence leads to technology and the lifetime of a technological civilization. Taking an optimistic view of the development of life and intelligence leads to the conclusion that the total number of technologically competent civilizations in the Galaxy is approximately equal to the lifetime of a typical civilization, expressed in years.



LO5 A technological civilization would probably "announce" itself to the universe by the radio and television signals it emits into space. Observed from afar, our planet would appear as a radio source with a 24-hour period, as different regions of the planet rise and set. The **water hole** (p. 518) is a region in the radio range of the electromagnetic spectrum, near the 21-cm line of hydrogen and the 18-cm line of hydroxyl, where natural emissions from the Galaxy happen to be minimal. Many researchers regard this as the best part of the spectrum for communications purposes.



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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 Why is life difficult to define?
2. What is chemical evolution?
3. What is the Urey-Miller experiment? What important organic molecules were produced in this experiment?
4. LO2 What are the basic ingredients from which biological molecules formed on Earth?
5. POS How do we know anything at all about the early episodes of life on Earth?
6. What is the role of language in cultural evolution?
7. Where else, besides Earth, have organic molecules been found?
8. LO3 Where—besides the planet Mars—might we find signs of life in our solar system?
9. POS Do we know whether Mars ever had life at any time during its past? What argues in favor of the position that it may once have harbored life?
10. POS What is generally meant by "life as we know it"? What other forms of life might be possible?
11. LO4 How many of the terms in the Drake equation are known with any-degree of certainty? Which factor is least well-known?
12. What is the relationship between the average lifetime of Galactic civilizations and the possibility of our someday communicating with them?
13. How would Earth appear, at radio wavelengths, to extraterrestrial astronomers?
14. What are the advantages of using radio waves for communication over interstellar distances?
15. LO5 What is the water hole? What advantage does it have over other parts of the radio spectrum?

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

1. The definition of life requires only that, to be considered "alive," you must be able to reproduce. (T/F)
2. Laboratory experiments have created living cells from nonbiological molecules. (T/F)
3. Dinosaurs lived on Earth for more than a thousand times longer than human civilization has existed to date. (T/F)
4. The *Viking* landers on Mars discovered microscopic evidence of life but found no fossil evidence. (T/F)
5. The development of life and intelligence on Earth are extremely unlikely if chance is the only evolutionary factor involved. (T/F)
6. We have no direct evidence for Earth-like planets orbiting other stars. (T/F)
7. Our civilization has already launched probes into interstellar space and broadcast our presence to our neighbors. (T/F)
8. The chemical elements that form the basic molecules needed for life are found (a) in the cores of Sun-like stars; (b) commonly throughout the cosmos; (c) only on planets that have liquid water; (d) only on Earth.
9. Fossil records of early life-forms on Earth suggest that life began about (a) 6000 years ago; (b) 65 million years ago; (c) 3.5 billion years ago; (d) 14 billion years ago.
10. The least well-known factor in the Drake equation is (a) the rate of star formation; (b) the fraction of stars having planetary systems; (c) the average lifetime of a technologically competent civilization; (d) the diameter of the Milky Way Galaxy.
11. We don't expect life on planets orbiting B-type stars because the star (a) has too much gravity; (b) is too short-lived for life to evolve; (c) is at too low a temperature to sustain life; (d) would have only gas giant planets.
12. NASA's Space Shuttle orbits Earth at about 17,500 mph. If it traveled to the next Sun-like star at that speed, the trip would take at least (a) 1 week; (b) 1 decade; (c) 1 century; (d) 100 millennia.
13. The strongest radio-wavelength emission in the solar system comes from (a) human-made signals from Earth; (b) the Sun; (c) the Moon; (d) Jupiter.
14. VIS From the data shown in Figure 18.11 (Stellar Habitable Zones), the habitable zone surrounding a main sequence K-type star (a) cannot be determined; (b) extends from roughly 1 to 2 AU from the star; (c) is larger than that of an F-type star; (d) is larger than that of an M-type star.
15. VIS If Figure 18.15 (Earth's Radio Leakage) were to be redrawn for a planet spinning twice as fast, the new jagged line would be (a) unchanged; (b) taller; (c) stretched out horizontally; (d) compressed horizontally.

PROBLEMS

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

1. ■ As described in the text, imagine that Earth's 4.6-billion-year age is compressed to just 46 years. What would be your age, in seconds? How long ago (in seconds) was the end of World War II, the Declaration of Independence, Columbus's discovery of the New World? How long ago did the extinction of the dinosaurs occur (in days)?
2. ■■■ According to the inverse-square law, a planet receives energy from its parent star at a rate proportional to the star's luminosity and inversely proportional to the square of the planet's distance from the star. ∞ *(Sec. 10.2)* According to Stefan's law, the rate at which the planet radiates energy into space is proportional to the fourth power of its surface temperature. ∞ *(Sec. 2.4)* In equilibrium, the two rates are equal. Based on this information and given the fact that (taking into account the greenhouse effect) the Sun's habitable zone extends from 0.6 AU to 1.5 AU, estimate the extent of the habitable zone surrounding a K-type main-sequence star of luminosity one-tenth the luminosity of the Sun.
3. ■ Based on the numbers presented in the text, and assuming an average lifetime of 5 billion years for suitable stars, estimate the total number of habitable planets in the Galaxy.
4. ■■ A planet orbits one component of a binary star system at a distance of 1 AU (see Figure 18.13a). If both stars have the same mass and their orbit is circular, estimate the minimum distance between the stars for the tidal force due to the companion not to exceed a "safe" 0.01 percent of the gravitational force between the planet and its parent star.
5. ■ Suppose that each of the "fraction" terms in the Drake equation turns out to have a value of 1/10, that stars form at an average rate of 20 per year, and that each star with a planetary system has exactly one habitable planet orbiting it. Estimate the present number of technological civilizations in the Milky Way Galaxy if the average lifetime of a civilization is (a) 100 years, (b) 10,000 years, (c) 1 million years.
6. ■■■ Adopting the estimate from the text that the number of technological civilizations in the Milky Way Galaxy is equal to the average lifetime of a civilization, in years, it follows that the distance to our nearest neighbor decreases as the average lifetime increases. Assuming that civilizations are uniformly spread over a two-dimensional Galactic disk of radius 15 kpc, and all have the same lifetime, calculate the *minimum* lifetime for which a two-way radio communication with our nearest neighbor would be possible before our civilization ends. Repeat the calculation for a round-trip personal visit, using current-technology spacecraft that travel at 50 km/s.
7. ■ How fast would a spacecraft have to travel in order to complete the trip from Earth to Alpha Centauri (a distance of 1.3 pc) and back in less than an average human lifetime (80 years, say)?
8. ■ Assuming that there are 10,000 FM radio stations on Earth, each transmitting at a power level of 50 kW, calculate the total radio luminosity of Earth in the FM band. Compare this value with the roughly 10^6 W radiated by the Sun in the same frequency range.
9. ■ Convert the water hole's wavelengths to frequencies. For practical reasons, any search of the water hole must be broken up into channels, much as you find on a television, except these channels are very narrow in radio frequency, about 100 Hz wide. How many channels must astronomers search in the water hole?
10. ■ There are 20,000 stars within 100 light-years that are to be searched for radio communications. How long will the search take if 1 hour is spent looking at each star? What if 1 day is spent per star?

ACTIVITIES

Collaborative

1. As a group, compose a paragraph everyone agrees with that defines life. It should clearly show that rocks are not alive and that plants are alive. According to your definition, are stars alive? What about viruses? Compare and contrast your group's definition with that from another group.
2. Independently, each person in your group should estimate the average lifetime of a technologically competent civilization, as used in the Drake equation. Explain the variation in your estimates.
3. If your group was appointed to "speak for Earth" upon establishing communication with an extraterrestrial world, what would you say? What questions would you ask, and what aspects of our planet would you choose to present? Write your group's speech and annotate it with explanations of why you chose to say this.

Individual

1. It has been suggested that if extraterrestrial life is discovered, it will have a profound effect on human culture. Interview as many people as you can and ask the following two questions: (1) Do you think that extraterrestrial life exists? (2) Why? From your results, try to decide whether the discovery of extraterrestrial life would indeed profoundly affect life on Earth.
2. Conduct another poll separately, or do it at the same time as the first one. Ask the following question: What one question would you like to ask an extraterrestrial life-form in a radio communication? How many responses do you receive that indicate "Earth-centered" thinking? How many responses suggest a lack of understanding of how alien an extraterrestrial life-form might be? Does this change your conclusion from the first project in any way?
3. The Drake equation should be able to "predict" at least one civilization in our Galaxy: us. Try changing the values of various factors so that you end up with at least one. What do these various combinations of factors imply about how life arises and develops? Are there some combinations that just don't make any sense?

APPENDIX 1

Scientific Notation

The objects studied by astronomers range in size from the smallest particles to the largest expanse of matter we know—the entire universe. Subatomic particles have sizes of about 0.000000000000001 meter, while galaxies typically measure some 1,000,000,000,000,000,000,000 meters across. The most distant known objects in the universe lie on the order of 100,000,000,000,000,000,000,000,000 meters from Earth.

Obviously, writing all those zeros is both cumbersome and inconvenient. More important, it is also very easy to make an error—write down one zero too many or too few and your calculations become hopelessly wrong! To avoid this, scientists always write large numbers using a shorthand notation in which the number of zeros following or preceding the decimal point is denoted by a superscript power, or *exponent*, of 10. The exponent is simply the number of places between the first significant (nonzero) digit in the number (reading from left to right) and the decimal point. Thus 1 is 10^0, 10 is 10^1, 100 is 10^2, 1000 is 10^3, and so on. For numbers less than 1, with zeros between the decimal point and the first significant digit, the exponent is negative: 0.1 is 10^{-1}, 0.01 is 10^{-2}, 0.001 is 10^{-3}, and so on. Using this notation we can shorten the number describing subatomic particles to 10^{-15} meter and write the number describing the size of a galaxy as 10^{21} meters.

More complicated numbers are expressed as a combination of a power of 10 and a multiplying factor. This factor is conventionally chosen to be a number between 1 and 10, starting with the first significant digit in the original number. For example, 150,000,000,000 meters (the distance from Earth to the Sun, in round numbers) can be more concisely written at 1.5×10^{11} meters, 0.000000025 meters as 2.5×10^{-8} meter, and so on. The exponent is simply the number of places the decimal point must be moved *to the left* to obtain the multiplying factor.

Some other examples of scientific notation are:

- the approximate distance to the Andromeda Galaxy $= 2{,}500{,}000$ light-years $= 2.5 \times 10^6$ light-years
- the size of a hydrogen atom $= 0.00000000005$ meter $= 5 \times 10^{-11}$ meter
- the diameter of the Sun $= 1{,}392{,}000$ kilometers $= 1.392 \times 10^6$ kilometers
- the U.S. national debt (as of June 1, 2015) $= \$18{,}152{,}841{,}000.00 = \$18.152841$ trillion $= 1.8152841 \times 10^{13}$ dollars.

In addition to providing a simpler way of expressing very large or very small numbers, this notation also makes it easier to do basic arithmetic. The rule for multiplication of numbers expressed in this way is simple: Just multiply the factors and add the exponents. Similarly for division, divide the factors and subtract the exponents. Thus, 3.5×10^{-2} multiplied by 2.0×10^3 is simply $(3.5 \times 2.0) \times 10^{-2+3} = 7.0 \times 10^1$—that is, 70. Again, 5×10^6 divided by 2×10^4 is just $(5/2) \times 10^{6-4}$, or 2.5×10^2 (= 250). Applying these rules to unit conversions, 200,000 nanometers is $200{,}000 \times 10^{-9}$ meter (since 1 nanometer $= 10^{-9}$ meter; see Appendix 2), or $(2 \times 10^5) \times 10^{-9}$ meter, or $2 \times 10^{5-9} = 2 \times 10^{-4}$ meter $= 0.2$ mm. Verify these rules yourself with a few examples of your own. The advantages of this notation when considering astronomical objects will soon become obvious.

Scientists often use "rounded-off" versions of numbers, both for simplicity and for ease of calculation. For example, we will usually write the diameter of the Sun as 1.4×10^6 kilometers, instead of the more precise number given earlier. Similarly, the diameter of Earth is 12,756 kilometers, or 1.2756×10^4 kilometers, but for "ballpark" estimates, we really don't need so many digits, and the more approximate number 1.3×10^4 kilometers will suffice. Very often, we perform rough calculations using only the first one or two significant digits in a number, and that may be all that is necessary to make a particular point. For example, to support the statement, "The Sun is much larger than Earth," we need only say that the ratio of the two diameters is roughly 1.4×10^6 divided by 1.3×10^4. Since 1.4/1.3 is close to 1, the ratio is approximately $10^6/10^4 = 10^2$, or 100. The essential fact here is that the ratio is much larger than 1; calculating it to greater accuracy (to get 109.13) would give us no additional *useful* information. This technique of stripping away the arithmetic details to get to the essence of a calculation is very common in astronomy, and we use it frequently throughout this text.

APPENDIX 2

Astronomical Measurement

Astronomers use many different kinds of units in their work, simply because no single system of units will do. Rather than the *Système Internationale* (SI), or meter-kilogram-second (MKS), metric system used in most high school and college science classes, many professional astronomers still prefer the older centimeter-gram-second (CGS) system. However, astronomers also commonly introduce new units when convenient. For example, when discussing stars, the mass and radius of the Sun are often used as reference points. The solar mass, written as $M_\odot$, is equal to 2.0×10^{33} g, or 2.0×10^{30} kg (since 1 kg = 1000 g). The solar radius, $R_\odot$, is equal to 700,000 km, or 7.0×10^8 m (1 km = 1000 m). The subscript $\odot$ always stands for Sun. Similarly, the subscript $\oplus$ always stands for Earth. In this book, we try to use the units that astronomers commonly use in any given context, but we also give the "standard" SI equivalents where appropriate.

Of particular importance are the units of length astronomers use. On small scales, the *angstrom* (1Å = 10^{-10} m = 10^{-8} cm), the *nanometer* (1 nm = 10^{-9} m = 10^{-7} cm), and the *micron* (1 μm = 10^{-6} m = 10^{-4} cm) are used. Distances within the solar system are usually expressed in terms of the *astronomical unit* (AU), the mean distance between Earth and the Sun. One AU is approximately equal to 150,000,000 km, or 1.5×10^{11} m. On larger scales, the *light-year* (1 ly = 9.5×10^{15} m = 9.5×10^{12} km) and the *parsec* (1 pc = 3.1×10^{16} m = 3.1×10^{13} km = 3.3 ly) are commonly used. Still larger distances use the regular prefixes of the metric system: *kilo* for one thousand and mega for one million. Thus 1 kiloparsec (kpc) = 10^3 pc = 3.1×10^{19} m, 10 megaparsecs (Mpc) = 10^7 pc = 3.1×10^{23} m, and so on.

Astronomers use units that make sense within a context, and as contexts change, so do the units. For example, we might measure densities in grams per cubic centimeter (g/cm^3), in atoms per cubic meter (atoms/m^3), or even in solar masses per cubic megaparsec ($M_\odot$/Mpc^3), depending on the circumstances. The important thing to know is that once you understand the units, you can convert freely from one set to another. For example, the radius of the Sun could equally well be written as $R_\odot = 6.96 \times 10^8$ m, or 6.96×10^{10} cm, or 109 $R_\oplus$, or 4.65×10^{-3} AU, or even 7.36×10^{-8} ly—whichever happens to be most useful. Some of the more common units used in astronomy, and the contexts in which they are most likely to be encountered, are listed below.

Length:

1 angstrom (Å) 1 nanometer (nm)	= 10^{-10} m = 10^{-9} m	atomic physics, spectroscopy
1 micron (μm)	= 10^{-6} m	interstellar dust and gas
1 centimeter (cm) 1 meter (m) 1 kilometer (km)	= 0.01 m = 100 cm = 1000 m = 10^5 cm	in widespread use throughout all astronomy
Earth radius ($R_\oplus$)	= 6378 km	planetary astronomy
Solar radius ($R_\odot$) 1 astronomical unit (AU)	= 6.96×10^8 m = 1.496×10^{11} m	solar system, stellar evolution
1 light-year (ly) 1 parsec (pc)	= 9.46×10^{15} m = 63,200 AU = 3.09×10^{16} m = 206,000 AU = 3.26 ly	galactic astronomy, stars and star clusters
1 kiloparsec (kpc) 1 megaparsec (Mpc)	= 1000 pc = 1000 kpc	galaxies, galaxy clusters, cosmology

Mass:

1 gram (g) 1 kilogram (kg)	=1000 g	in widespread use in many different areas
Earth mass ($M_\oplus$)	=5.98×10^{24} kg	planetary astronomy
Solar mass ($M_\odot$)	=1.99×10^{30} kg	"standard" unit for all mass scales larger than Earth

Time:

1 second (s)		in widespread use throughout astronomy
1 hour (h) 1 day (d)	=3600 s =86,400 s	planetary and stellar scales
1 year (yr)	=3.16×10^7 s	virtually all processes occurring on scales larger than a star

APPENDIX 3

Tables

TABLE 1 Some Useful Constants and Physical Measurements[1]

astronomical unit	1 AU $= 1.496 \times 10^8$ km (1.5×10^8 km)
light-year	1 ly $= 9.46 \times 10^{12}$ km (10^{13} km; about 6 trillion miles)
parsec	1 pc $= 3.09 \times 10^{13}$ km $= 3.3$ ly
speed of light	$c = 299{,}792.458$ km/s (3×10^5 km/s)
Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8}$ W/m$^2 \cdot$K^4
gravitational constant	$G = 6.67 \times 10^{-11}$ N m^2/kg^2
mass of Earth	$M_\oplus = 5.97 \times 10^{24}$ kg (6×10^{24} kg; 6000 billion tons)
radius of Earth	$R_\oplus = 6378$ km (6500 km)
mass of the Sun	$M_\odot = 1.99 \times 10^{30}$ kg (2×10^{30} kg)
radius of the Sun	$R_\odot = 6.96 \times 10^5$ km (7×10^5 km)
luminosity of the Sun	$L_\odot = 3.90 \times 10^{26}$ W (4×10^{26} W)
effective temperature of the Sun	$T_\odot = 5778$ K (5800 K)
Hubble constant	$H_0 \approx 70$ km/s/Mpc
mass of an electron	$m_e = 9.11 \times 10^{-31}$ kg
mass of a proton	$m_p = 1.67 \times 10^{-27}$ kg

[1] The rounded-off values used in the text are shown above in parentheses.

Conversions Between Common English and Metric Units

English	Metric
1 inch	= 2.54 centimeters (cm)
1 foot (ft)	= 0.3048 meters (m)
1 mile	= 1.609 kilometers (km)
1 pound (lb)	= 453.6 grams (g) or 0.4536 kilograms (kg) (on Earth)

TABLE 2 Main-Sequence Stellar Properties by Spectral Class

Spectral Class	Typical Surface Temperature	Color	Mass*	Luminosity*	Lifetime*	Familiar Examples
	(K)		($M_\odot$)	($L_\odot$)	(10^6 yr)	
O	>30,000	Electric Blue	>20	>100,000	<2	Mintaka (O9)
B	20,000	Blue	7	500	140	Spica (B2)
A	10,000	White	3	60	500	Vega (A0) Sirius (A1)
F	7000	Yellow-white	1.5	7	2000	Procyon (F5)
G	6000	Yellow	1.0	1.0	10,000	Sun (G2) Alpha Centauri (G2)
K	4000	Orange	0.8	0.3	30,000	Epsilon Eridani (K2)
M	3000	Red	0.1	0.00006	16,000,000	Proxima Centauri (M5) Barnard's Star (M5)

*Approximate values for stars of solar composition

TABLE 3A Planetary Data: Orbital Properties

Planet	Semimajor Axis (AU)	Semimajor Axis (10^6 km)	Sidereal Period (tropical years)	Mean Orbital Speed (km/s)	Orbital Eccentricity	Inclination to the Ecliptic (degrees)
Mercury	0.39	57.9	0.241	47.9	0.206	7.00
Venus	0.72	108.2	0.612	35.0	0.007	3.39
Earth	1.00	149.6	1.00	29.8	0.017	0.01
Mars	1.52	227.9	1.88	24.1	0.093	1.85
Jupiter	5.20	778.4	11.86	13.1	0.048	1.31
Saturn	9.54	1427	29.42	9.65	0.054	2.49
Uranus	19.19	2871	83.75	6.80	0.047	0.77
Neptune	30.07	4498	163.7	5.43	0.009	1.77

TABLE 3B Planetary Data: Physical Properties

Planet	Equatorial Radius (km)	Equatorial Radius (Earth = 1)	Mass (kg)	Mass (Earth = 1)	Mean Density (kg/m^3)	Sidereal Rotation Period (solar days)[1]
Mercury	2440	0.38	3.30×10^{23}	0.055	5430	58.6
Venus	6052	0.95	4.87×10^{24}	0.82	5240	−243.0
Earth	6378	1.00	5.97×10^{24}	1.00	5520	0.9973
Mars	3394	0.53	6.42×10^{23}	0.11	3930	1.026
Jupiter	71,492	11.21	1.90×10^{27}	317.8	1330	0.41
Saturn	60,268	9.45	5.68×10^{26}	95.2	690	0.44
Uranus	25,559	4.01	8.68×10^{25}	14.5	1270	−0.72
Neptune	24,766	3.88	1.02×10^{26}	17.1	1640	0.67

Planet	Axial Tilt (degrees)	Surface Gravity (Earth = 1)	Escape Speed (km/s)	Surface Temperature (K)[2]	Number of Moons[3]
Mercury	0.0	0.38	4.2	100 to 700	0
Venus	177.4	0.91	10.4	730	0
Earth	23.5	1.00	11.2	290	1
Mars	24.0	0.38	5.0	180 to 270	2
Jupiter	3.1	2.53	60	124	16
Saturn	26.7	1.07	36	97	18
Uranus	97.9	0.91	21	58	27
Neptune	29.6	1.14	24	59	13

[1]A negative sign indicates retrograde rotation.

[2]Temperature is effective temperature for jovian planets.

[3]Moons more than 10 km in diameter

TABLE 4 The 20 Brightest Stars in Earth's Night Sky

Name	Star	Spectral Type* A	Spectral Type* B	Parallax (arc seconds)	Distance (pc)	Apparent Visual Magnitude* A	Apparent Visual Magnitude* B
Sirius	α CMa	A1V	wd†	0.379	2.6	−1.44	+8.4
Canopus	α Car	F0Ib–II		0.010	96	−0.62	
Arcturus	α Boo	K2III		0.089	11	−0.05	
Rigel Kentaurus (Alpha Centauri)	α Cen	G2V	K0V	0.742	1.3	−0.01	+1.4
Vega	α Lyr	A0V		0.129	7.8	+0.03	
Capella	α Aur	GIII	M1V	0.077	13	+0.08	+10.2
Rigel	β Ori	B8Ia	B9	0.0042	240	+0.18	+6.6
Procyon	α CMi	F5IV–V	Wd†	0.286	3.5	+0.40	+10.7
Betelgeuse	α Ori	M2Iab		0.0076	130	+0.45	
Achernar	α Eri	B5V		0.023	44	+0.45	
Hadar	α Cen	B1III	?	0.0062	160	+0.61	+4
Altair	α Aq1	A7IV–V		0.194	5.1	+0.76	
Acrux	α Cru	B1IV	B3	0.010	98	+0.77	+1.9
Aldebaran	α Tau	K5III	M2V	0.050	20	+0.87	+13
Spica	α Vir	B1V	B2V	0.012	80	+0.98	2.1
Antares	α Sco	M1Ib	B4V	0.005	190	+1.06	+5.1
Pollux	β Gem	K0III		0.097	10	+1.16	
Formalhaut	α PsA	A3V	?	0.130	7.7	+1.17	+6.5
Deneb	α Cyg	A2Ia		0.0010	990	+1.25	
Mimosa	β Cru	B1IV		0.0093	110	+1.25	

Name	Visual Luminosity* (Sun = 1) A	Visual Luminosity* (Sun = 1) B	Absolute Visual Magnitude[1] A	Absolute Visual Magnitude[1] B	Proper Motion (arc seconds/yr)	Transverse Velocity (km/s)	Radial Velocity (km/s)
Sirius	22	0.0025	+1.5	+11.3	1.33	16.7	−7.6‡
Canopus	4.1×10^4		−5.5		0.02	9.1	20.5
Arcturus	110		−0.3		2.28	119	−5.2
Rigel Kentaurus	1.6	0.45	+4.3	+5.7	3.68	22.7	−24.6
Vega	50		+0.6		0.34	12.6	−13.9
Capella	130	0.01	−0.5	+9.6	0.44	27.1	30.2‡
Rigel	4.1×10^4	110	−6.7	−0.3	0.00	1.2	20.7
Procyon	7.2	0.0006	+2.7	+13.0	1.25	20.7	−3.2
Betelgeuse	9700		−5.1		0.03	18.5	21.0
Achernar	1100		−2.8		0.10	20.9	19
Hadar	1.3×10^4	560	−5.4	−2.0	0.04	30.3	−12
Altair	11		+2.2		0.66	16.3	−26.3
Acrux	4100	2200	−4.2	−3.5	0.04	22.8	−11.2
Aldebaran	150	0.002	−0.6	+11.5	0.20	19.0	54.1
Spica	2200	780	−3.5	−2.4	0.05	19.0	1.0
Antares	1.1×10^4	290	−5.3	−1.3	0.03	27.0	−3.2
Pollux	31		+1.1		0.62	29.4	3.3
Formalhaut	17	0.13	+1.7	+7.1	0.37	13.5	6.5
Deneb	2.6×10^5		−8.7		0.003	14.1	−4.6
Mimosa	3200		−3.9		0.05	26.1	–

* Energy output in the visible part of the spectrum; A and B columns identify individual components of binary star systems.

† "wd" stands for "white dwarf."

‡ Average value of variable velocity

TABLE 5 The 20 Nearest Stars

Name	Spectral Type* A	Spectral Type* B	Parallax (arc seconds)	Distance (pc)	Apparent Visual Magnitude* A	Apparent Visual Magnitude* B
Sun	G2V				−26.74	
Proxima Centauri	M5		0.772	1.30	+11.01	
Alpha Centauri	G2V	K1V	0.742	1.35	−0.01	+1.35
Barnard's Star	M5V		0.549	1.82	+9.54	
Wolf 359	M8V		0.421	2.38	+13.53	
Lalande 21185	M2V		0.397	2.52	+7.50	
UV Ceti	M6V	M6V	0.387	2.58	+12.52	+13.02
Sirius	A1V	wd†	0.379	2.64	−1.44	+8.4
Ross 154	M5V		0.345	2.90	+10.45	
Ross 248	M6V		0.314	3.18	+12.29	
ε Eridani	K2V		0.311	3.22	+3.72	
Ross 128	M5V		0.298	3.36	+11.10	
61 Cygni	K5V	K7V	0.294	3.40	+5.22	+6.03
ε Indi	K5V		0.291	3.44	+4.68	
Grm 34	M1V	M6V	0.290	3.45	+8.08	+11.06
Luyten 789-6	M6V		0.290	3.45	+12.18	
Procyon	F5IV–V	wd†	0.286	3.50	+0.40	+10.7
Σ 2398	M4V	M5V	0.285	3.55	+8.90	+9.69
Lacaille 9352	M2V		0.279	3.58	+7.35	
G51-15	MV		0.278	3.60	+14.81	

Name	Visual Luminosity* (Sun = 1) A	Visual Luminosity* (Sun = 1) B	Absolute Visual Magnitude* A	Absolute Visual Magnitude* B	Proper Motion (arc seconds/yr)	Transverse Velocity (km/s)	Radial Velocity (km/s)
Sun	1.0		+4.83				
Proxima Centauri	5.6×10^{-5}		+15.4		3.86	23.8	−16
Alpha Centauri	1.6	0.45	+4.3	+5.7	3.68	23.2	−22
Barnard's Star	4.3×10^{-4}		+13.2		10.34	89.7	−108
Wolf 359	1.8×10^{-5}		+16.7		4.70	53.0	+13
Lalande 21185	0.0055		+10.5		4.78	57.1	−84
UV Ceti	5.4×10^{-4}	0.00004	+15.5	+16.0	3.36	41.1	+30
Sirius	22	0.0025	+1.5	+11.3	1.33	16.7	−8
Ross 154	4.8×10^{-4}		+13.3		0.72	9.9	−4
Ross 248	1.1×10^{-4}		+14.8		1.58	23.8	−81
ε Eridani	0.29		+6.2		0.98	15.3	+16
Ross 128	3.6×10^{-4}		+13.5		1.37	21.8	−13
61 Cygni	0.082	0.039	+7.6	+8.4	5.22	84.1	−64
ε Indi	0.14		+7.0		4.69	76.5	−40
Grm 34	0.0061	0.00039	+10.4	+13.4	2.89	47.3	+17
Luyten 789-6	1.4×10^{-4}		+14.6		3.26	53.3	−60
Procyon	7.2	0.00055	+2.7	+13.0	1.25	2.8	−3
Σ 2398	0.0030	0.0015	+11.2	+11.9	2.28	38.4	+5
Lacaille 9352	0.013		+9.6		6.90	117	+10
G51-15	1.4×10^{-5}		+17.0		1.26	21.5	—

* A and B columns identify individual components of binary star systems.

† "wd" stands for "white dwarf."

Glossary

Key terms that are boldface in the text are followed by a page reference in the Glossary.

A

A ring One of three Saturnian rings visible from Earth. The A ring is farthest from the planet and is separated from the B ring by the Cassini Division. (p. 238)

aberration of starlight Small shift in the observed direction to a star, caused by Earth's motion perpendicular to the line of sight.

absolute brightness The apparent brightness a star would have if it were placed at a standard distance of 10 parsecs from Earth.

absolute magnitude The apparent magnitude a star would have if it were placed at a standard distance of 10 parsecs from Earth. (p. 284)

absolute zero The lowest possible temperature that can be obtained; all thermal motion ceases at this temperature.

absorption line Dark line in an otherwise continuous bright spectrum, where light within one narrow frequency range has been removed. (p. 57)

abundance Relative amounts of different elements in a gas.

acceleration The rate of change of velocity of a moving object. (p. 38)

accretion Gradual growth of bodies, such as planets, by the accumulation of other, smaller bodies. (p. 123)

accretion disk Flat disk of matter spiraling down onto the surface of a neutron star or black hole. Often, the matter originated on the surface of a companion star in a binary star system. (p. 341)

active galactic nucleus Region of intense emission at the center of an active galaxy responsible for virtually all of the galaxy's nonstellar luminosity. (p. 433)

active galaxies The most energetic galaxies, which can emit hundreds or thousands of times more energy per second than the Milky Way, mostly in the form of long-wavelength nonthermal radiation. (p. 432)

active optics Collection of techniques used to increase the resolution of ground-based telescopes. Minute modifications are made to the overall configuration of an instrument as its temperature and orientation change; used to maintain the best possible focus at all times. (p. 84)

active region Region of the photosphere of the Sun surrounding a sunspot group, which can erupt violently and unpredictably. During sunspot maximum, the number of active regions is also a maximum. (p. 266)

active Sun The unpredictable aspects of the Sun's behavior, such as sudden explosive outbursts of radiation in the form of prominences and flares.

adaptive optics Technique used to increase the resolution of a telescope by deforming the shape of the mirror's surface under computer control while a measurement is being taken; used to undo the effects of atmospheric turbulence. (p. 84)

aerosol Suspension of liquid or solid particles in air.

alpha particle A helium-4 nucleus.

alpha process Process occurring at high temperatures, in which high-energy photons split heavy nuclei to form helium nuclei.

ALSEP Acronym for Apollo Lunar Surface Experiments Package.

altimeter Instrument used to determine altitude.

amino acids Organic molecules that form the basis for building the proteins that direct metabolism in living creatures. (p. 505)

Amor asteroid Asteroid that crosses only the orbit of Mars.

amplitude The maximum deviation of a wave above or below zero point. (p. 47)

angstrom Distance unit equal to 0.1 nanometers, or one 10-billionth of a meter.

angular diameter Angle made between the top (or one edge) of an object, the observer and the bottom (or opposite edge) of the object.

angular distance Angular separation between two objects as seen by some observer.

angular momentum Tendency of an object to keep rotating; proportional to the mass, radius, and rotation speed of the body.

angular resolution The ability of a telescope to distinguish between adjacent objects in the sky. (p. 81)

annular eclipse Solar eclipse occurring at a time when the Moon is far enough away from Earth that it fails to cover the disk of the Sun completely, leaving a ring of sunlight visible around its edge. (p. 16)

antiparallel Configuration of the electron and proton in a hydrogen (or other) atom when their spin axes are parallel but the two rotate in opposite directions.

antiparticle A particle of the same mass but opposite in all other respects (e.g., charge) to a given particle; when a particle and its antiparticle come into contact, they annihilate and release energy in the form of gamma rays.

aphelion The point on the elliptical path of an object in orbit about the Sun that is most distant from the Sun. (p. 35)

Apollo asteroid *See* Earth-crossing asteroid.

apparent brightness The brightness that a star appears to have, as measured by an observer on Earth. (p. 282)

apparent magnitude The apparent brightness of a star, expressed using the magnitude scale. (p. 284)

association Small grouping of (typically 100 or less) bright stars, spanning up to a few tens of parsecs across, usually rich in very young stars. (p. 324)

Assumption of Mediocrity Statements suggesting that the development of life on Earth did not require any unusual circumstances, suggesting that extraterrestrial life may be common.

asteroid One of thousands of very small members of the solar system orbiting the Sun between the orbits of Mars and Jupiter. Often referred to as "minor planets." (p. 107)

asteroid belt Region of the solar system, between the orbits of Mars and Jupiter, in which most asteroids are found. (p. 108)

asthenosphere Layer of Earth's interior, just below the lithosphere, over which the surface plates slide.

astrology Pseudoscience that purports to use the positions of the planets, sun, and moon to predict daily events and human destiny.

astronomical unit (AU) The average distance of Earth from the Sun. Precise radar measurements yield a value for the AU of 149,603,500 km. (p. 35)

astronomy Branch of science dedicated to the study of everything in the universe that lies above Earth's atmosphere. (p. 6)

asymptotic giant branch Path on the Hertzsprung–Russell diagram corresponding to the changes that a star undergoes after helium burning ceases in the core. At this stage, the carbon core shrinks and drives the expansion of the envelope, and the star becomes a swollen red giant for a second time.

aten asteroid Earth-crossing asteroid with semimajor axis less than 1 AU.

atmosphere Layer of gas confined close to a planet's surface by the force of gravity. (p. 140)

atom Building block of matter, composed of positively charged protons and neutral neutrons in the nucleus surrounded by negatively charged electrons. (p. 60)

atomic epoch Period after decoupling when the first simple atoms and molecules formed.

aurora Event that occurs when atmospheric molecules are excited by incoming charged particles from the solar wind, then emit energy as they fall back to their ground states. Aurorae generally occur at high latitudes, near the north and south magnetic poles. (p. 160)

autumnal equinox Date on which the Sun crosses the celestial equator moving southward, occurring on or near September 22. (p. 12)

B

B ring One of three Saturnian rings visible from Earth. The B ring is the brightest of the three and lies just past the Cassini Division, closer to the planet than the A ring. (p. 238)

background noise Unwanted light in an image, from unresolved sources in the telescope's field of view, scattered light from the atmosphere, or instrumental "hiss" in the detector itself.

barred-spiral galaxy Spiral galaxy in which a bar of material passes through the center of the galaxy, with the spiral arms beginning near the ends of the bar. (p. 422)

basalt Solidified lava; an iron-magnesium-silicate mixture.

baseline The distance between two observing locations used for the purposes of triangulation measurements. The larger the baseline, the better the resolution attainable. (p. 19)

belt Dark, low-pressure region in the atmosphere of a jovian planet, where gas flows downward. (p. 209)

Big Bang Event that cosmologists consider the beginning of the universe, in which all matter and radiation in the entire universe came into being. (p. 478)

Big Crunch Point of final collapse of a bound universe.

binary asteroid Asteroids that have a partner in orbit around it.

binary pulsar Binary system in which both components are pulsars.

binary-star system A system that consists of two stars in orbit about their common center of mass, held together by their mutual gravitational attraction. Most stars are found in binary-star systems. (p. 295)

biological evolution Change in a population of biological organisms over time.

bipolar flow Jets of material expelled from a protostar perpendicular to the surrounding protostellar disk.

blackbody curve The characteristic way in which the intensity of radiation emitted by a hot object depends on frequency. The frequency at which the emitted intensity is highest is an indication of the temperature of the radiating object. Also referred to as the Planck curve. (p. 53)

black dwarf The endpoint of the evolution of an isolated, low-mass star. After the white dwarf stage, the star cools to the point where it is a dark "clinker" in interstellar space. (p. 339)

black hole A region of space where the pull of gravity is so great that nothing—not even light—can escape. A possible outcome of the evolution of a very massive star. (p. 373)

blazar Particularly intense active galactic nucleus in which the observer's line of sight happens to lie directly along the axis of a high-speed jet of particles emitted from the active region. (p. 437)

blue giant Large, hot, bright star at the upper-left end of the main sequence on the Hertzsprung–Russell diagram. Its name comes from its color and size. (p. 290)

blueshift Motion-induced changes in the observed wavelength from a source that is moving toward us. Relative approaching motion between the object and the observer causes the wavelength to appear shorter (and hence bluer) than if there were no motion at all.

blue straggler Star found on the main sequence of the Hertzsprung–Russell diagram, but which should already have evolved off the main sequence, given its location on the diagram; thought to have formed from mergers of lower mass stars.

blue supergiant The very largest of the large, hot, bright stars at the uppermost-left end of the main sequence on the Hertzsprung–Russell diagram. (p. 290)

Bohr model First theory of the hydrogen atom to explain the observed spectral lines. This model rests on three ideas: that there is a state of lowest energy for the electron, that there is a maximum energy beyond which the electron is no longer bound to the nucleus, and that within these two energies the electron can only exist in certain energy levels. (p. 60)

bok globule Dense, compact cloud of interstellar dust and gas on its way to forming one or more stars.

boson Particle that exerts or mediates forces between elementary particles in quantum physics.

bound trajectory Path of an object with launch speed low enough that it cannot escape the gravitational pull of a planet.

brown dwarf Remnants of fragments of collapsing gas and dust that did not contain enough mass to initiate core nuclear fusion. Such objects are then frozen somewhere along their pre-main-sequence contraction phase, continually cooling into compact dark objects. Because of their small size and low temperature, they are extremely difficult to detect observationally. (p. 322)

brown oval Feature of Jupiter's atmosphere that appears only at latitudes near 20 degrees N, this structure is a long-lived hole in the clouds that allows us to look down into Jupiter's lower atmosphere. (p. 211)

C

C ring One of three Saturnian rings visible from Earth. The C ring lies closest to the planet and is relatively thin compared to the A and B rings. (p. 238)

caldera Crater that forms at the summit of a volcano.

capture theory (Moon) Theory suggesting that the Moon formed far from Earth but was later captured by it.

carbonaceous asteroid The darkest, or least reflective, type of asteroid, containing large amounts of carbon.

carbon-based molecule Molecule containing atoms of carbon.

carbon-detonation supernova *See* Type I supernova. (p. 346)

cascade Process of deexcitation in which an excited electron moves down through energy states one at a time.

Cassegrain telescope A type of reflecting telescope in which incoming light hits the primary mirror and is then reflected upward toward the prime focus, where a secondary mirror reflects the light back down through a small hole in the main mirror into a detector or eyepiece. (p. 74)

Cassini Division A relatively empty gap in Saturn's ring system, discovered in 1675 by Giovanni Cassini. It is now known to contain a number of thin ringlets. (p. 238)

cataclysmic variable Collective name for novae and supernovae.

catalyst Something that causes or helps a reaction to occur, but is not itself consumed as part of the reaction.

catastrophic theory A theory that invokes statistically unlikely accidental events to account for observations.

celestial coordinates Pair of quantities—right ascension and declination—similar to longitude and latitude on Earth, used to pinpoint locations of objects on the celestial sphere. (p. 8)

celestial equator The projection of Earth's equator onto the celestial sphere. (p. 8)

celestial mechanics Study of the motions of bodies, such as planets and stars, that interact via gravity.

celestial pole Projection of Earth's North or South pole onto the celestial sphere.

celestial sphere Imaginary sphere surrounding Earth to which all objects in the sky were once considered to be attached. (p. 7)

Celsius Temperature scale in which the freezing point of water is 0 degrees and the boiling point of water is 100 degrees.

center of mass The "average" position in space of a collection of massive bodies, weighted by their masses. For an isolated system this point moves with constant velocity, according to Newtonian mechanics. (p. 40)

centigrade *See* Celsius.

centripetal force (literally "center seeking") Force directed toward the center of a body's orbit.

centroid Average position of the material in an object; in spectroscopy, the center of a spectral line.

Cepheid variable Star whose luminosity varies in a characteristic way, with a rapid rise in brightness followed by a slower decline. The period of a Cepheid variable star is related to its luminosity, so a determination of this period can be used to obtain an estimate of the star's distance. (p. 394)

Chandrasekhar mass Maximum possible mass of a white dwarf.

chaotic rotation Unpredictable tumbling motion that nonspherical bodies in eccentric orbits, such as Saturn's satellite Hyperion, can exhibit. No amount of observation of an object rotating chaotically will ever show a well-defined period.

charge-coupled device (CCD) An electronic device used for data acquisition; composed of many tiny pixels, each of which records a buildup of charge to measure the amount of light striking it. (p. 78)

chemical bond Force holding atoms together to form a molecule.

chemosynthesis Analog of photosynthesis that operates in total darkness.

chromatic aberration The tendency for a lens to focus red and blue light differently, causing images to become blurred.

chromosphere The Sun's lower atmosphere, lying just above the visible atmosphere. (p. 254)

circumnavigation Traveling all the way around an object.

cirrus High-level clouds composed of ice or methane crystals.

closed universe Geometry that the universe as a whole would have if the density of matter is above the critical value. A closed universe is finite in extent and has no edge, like the surface of a sphere. It has enough mass to stop the present expansion and will eventually collapse. (p. 481)

CNO cycle Chain of reactions that converts hydrogen into helium using carbon, nitrogen, and oxygen as catalysts.

cocoon nebula Bright infrared source in which a surrounding cloud of gas and dust absorb ultraviolet radiation from a hot star and reemits it in the infrared.

cold dark matter Class of dark-matter candidates made up of very heavy particles, possibly formed in the very early universe.

collecting area The total area of a telescope capable of capturing incoming radiation. The larger the telescope, the greater its collecting area and the fainter the objects it can detect. (p. 79)

collisional broadening Broadening of spectral lines due to collisions between atoms, most often seen in dense gases.

color index A convenient method of quantifying a star's color by comparing its apparent brightness as measured through different filters. If the star's radiation is well described by a blackbody spectrum, the ratio of its blue intensity (B) to its visual intensity (V) is a measure of the object's surface temperature.

color–magnitude diagram A way of plotting stellar properties, in which absolute magnitude is plotted against color index.

coma An effect occurring during the formation of an off-axis image in a telescope. Stars whose light enters the telescope at a large angle acquire comet-like tails on their images. The brightest part of a comet, often referred to as the "head." (p. 112)

comet A small body, composed mainly of ice and dust, in an elliptical orbit about the Sun. As it comes close to the Sun, some of its material is vaporized to form a gaseous head and extended tail. (p. 107)

common envelope Outer layer of gas in a contact binary.

comparative planetology The systematic study of the similarities and differences among the planets, with the goal of obtaining deeper insight into how the solar system formed and has evolved in time.

composition The mixture of atoms and molecules that make up an object.

condensation nuclei Dust grains in the interstellar medium that act as seeds around which other material can cluster. The presence of dust was very important in causing matter to clump during the formation of the solar system. (p. 123)

condensation theory Currently favored model of solar system formation that combines features of the old nebular theory with new information about interstellar dust grains, which acted as condensation nuclei. (p. 122)

conjunction Orbital configuration in which a planet lies in the same direction as the Sun, as seen from Earth.

conservation of mass and energy *See* law of conservation of mass and energy.

constellation A human grouping of stars in the night sky into a recognizable pattern. (p. 6)

constituents *See* composition.

contact binary A binary star system in which both stars have expanded to fill their Roche lobes, and the surfaces of the two stars merge. The binary system now consists of two nuclear burning stellar cores surrounded by a continuous common envelope.

continental drift The movement of the continents around Earth's surface.

continuous spectra Spectra in which the radiation is distributed over all frequencies, not just a few specific frequency ranges. A prime example is the blackbody radiation emitted by a hot, dense body. (p. 56)

convection Churning motion resulting from the constant upwelling of warm fluid and the concurrent downward flow of cooler material to take its place. (p. 144)

convection cell Circulating region of upwelling hot fluid and sinking cooler fluid in convective motion. (p. 144)

convection zone Region of the Sun's interior, lying just below the surface, where the material of the Sun is in constant convection motion. This region extends into the solar interior to a depth of about 20,000 km. (p. 254)

co-orbital satellites Satellites sharing the same orbit around a planet.

Copernican principle The removal of Earth from any position of cosmic significance.

Copernican revolution The realization, toward the end of the 16th century, that Earth is not at the center of the universe. (p. 31)

core The central region of Earth, surrounded by the mantle. (p. 256)

The central region of any planet or star. (p. 256)

core-accretion theory Theory that the jovian planets formed when icy protoplanetary cores became massive enough to capture gas directly from the solar nebula. *See* gravitational instability theory.

core-collapse supernova *See* Type II supernova.

core hydrogen burning The energy-burning stage for main-sequence stars, in which the helium is produced by hydrogen fusion in the central region of the star. A typical star spends up to 90 percent of its lifetime in hydrostatic equilibrium brought about by the balance between gravity and the energy generated by core hydrogen burning. (p. 332)

cornea (eye) The curved transparent layer covering the front part of the eye. (p. 171)

corona One of numerous large, roughly circular regions on the surface of Venus, thought to have been caused by upwelling mantle material causing the planet's crust to bulge outward (plural, *coronae*). (p. 178)

The tenuous outer atmosphere of the Sun, which lies just above the chromosphere and, at great distances, turns into the solar wind. (p. 246)

coronal hole Vast regions of the Sun's atmosphere where the density of matter is about 10 times lower than average. The gas there streams freely into space at high speeds, escaping the Sun completely. (p. 268)

coronal mass ejection Giant magnetic "bubble" of ionized gas that separates from the rest of the solar atmosphere and escapes into interplanetary space. (p. 267)

corpuscular theory Early particle theory of light.

cosmic density parameter Ratio of the universe's actual density to the critical value corresponding to zero curvature.

cosmic distance scale Collection of indirect distance-measurement techniques that astronomers use to measure distances in the universe. (p. 18)

cosmic evolution The collection of the seven major phases of the history of the universe, namely particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. (p. 504)

cosmic microwave background The almost perfectly isotropic radio signal that is the electromagnetic remnant of the Big Bang. (p. 487)

cosmic ray Very energetic subatomic particle arriving at Earth from elsewhere in the Galaxy.

cosmological constant Quantity originally introduced by Einstein into general relativity to make his equations describe a static universe. Now one of several candidates for the repulsive "dark energy" force responsible for the observed cosmic acceleration. (p. 484)

cosmological distance Distance comparable to the scale of the universe.

cosmological principle Two assumptions that make up the basis of cosmology, namely that the universe is homogeneous and isotropic on sufficiently large scales. (p. 477)

cosmological redshift The component of the redshift of an object that is due only to the Hubble flow of the universe. (p. 431)

cosmology The study of the structure and evolution of the entire universe. (p. 477)

cosmos The universe.

coudé focus Focus produced far from the telescope using a series of mirrors. Allows the use of heavy and/or finely tuned equipment to analyze the image.

crater Bowl-shaped depression on the surface of a planet or moon, resulting from a collision with interplanetary debris. (p. 156)

crescent Appearance of the Moon (or a planet) when less than half of the body's hemisphere is visible from Earth.

crest Maximum departure of a wave above its undisturbed state.

critical density The cosmic density corresponding to the dividing line between a universe that recollapses and one that expands forever. (p. 480)

critical universe Universe in which the density of matter is exactly equal to the critical density. The universe is infinite in extent and has zero curvature. The expansion will continue forever, but will approach an expansion speed of zero. (p. 482)

crust Layer of Earth that contains the solid continents and the seafloor. (p. 140)

C-type asteroid *See* carbonaceous asteroid.

cultural evolution Change in the ideas and behavior of a society over time.

current sheet Flat sheet on Jupiter's magnetic equator where most of the charged particles in the magnetosphere lie due to the planet's rapid rotation.

D

D ring Collection of very faint, thin rings, extending from the inner edge of the C ring down nearly to the cloud tops of Saturn. This region contains so few particles that it is completely invisible from Earth. (p. 240)

dark dust cloud A large cloud, often many parsecs across, which contains gas and dust in a ratio of about 1012 gas atoms for every dust particle. Typical densities are a few tens or hundreds of millions of particles per cubic meter. (p. 311)

dark energy Generic name given to the unknown cosmic force field thought to be responsible for the observed acceleration of the Hubble expansion. (p. 483)

dark halo Region of a galaxy beyond the visible halo where dark matter is believed to reside. (p. 406)

dark matter Term used to describe the mass in galaxies and clusters whose existence we infer from rotation curves and other techniques, but that has not been confirmed by observations at any electromagnetic wavelength. (p. 406)

dark matter particle Particle undetectable at any electromagnetic wavelength, but can be inferred from its gravitational influence.

daughter/fission theory Theory suggesting that the Moon originated out of Earth.

declination Celestial coordinate used to measure latitude above or below the celestial equator on the celestial sphere. (p. 8)

decoupling Event in the early universe when atoms first formed, after which photons could propagate freely through space. (p. 491)

deferent A construct of the geocentric model of the solar system that was needed to explain observed planetary motions. A deferent is a large circle encircling Earth, on which an epicycle moves. (p. 29)

degree Unit of angular measure. There are 360 degrees in one complete circle.

density A measure of the compactness of the matter within an object, computed by dividing the mass of the object by its volume. Units are kilograms per cubic meter (kg/m^3), or grams per cubic centimeter (g/cm^3). (p. 105)

detached binary Binary system where each star lies within its respective Roche lobe.

detector noise Readings produced by an instrument even when it is not observing anything; produced by the electronic components within the detector itself.

deuterium A form of hydrogen with an extra neutron in its nucleus.

deuterium bottleneck Period in the early universe between the start of deuterium production and the time when the universe was cool enough for deuterium to survive.

deuteron An isotope of hydrogen in which a neutron is bound to the proton in the nucleus. Often called "heavy hydrogen" because of the extra mass of the neutron. (p. 271)

differential rotation The tendency for a gaseous sphere, such as a jovian planet or the Sun, to rotate at a different rate at the equator than at the poles. More generally, a condition where the angular speed varies with location within an object. (p. 207)

differentiation Variation in the density and composition of a body, such as Earth, with low-density material on the surface and higher-density material in the core. (p. 150)

diffraction The ability of waves to bend around corners. The diffraction of light establishes its wave nature. (p. 48)

diffraction grating Sheet of transparent material with many closely spaced parallel lines ruled on it, designed to separate white light into a spectrum.

diffraction-limited resolution Theoretical resolution that a telescope can have due to diffraction of light at the telescope's aperture. Depends on the wavelength of radiation and the diameter of the telescope's mirror. (p. 81)

direct motion *See* prograde motion.

distance modulus Difference between the apparent and absolute magnitude of an object; equivalent to distance, by the inverse-square law.

diurnal motion Apparent daily motion of the stars caused by Earth's rotation. (p. 9)

DNA Deoxyribonucleic acid, the molecule that carries genetic information and determines the characteristics of a living organism.

Doppler effect Any motion-induced change in the observed wavelength (or frequency) of a wave. (p. 64)

double-line spectroscopic binary Binary system in which spectral lines of both stars can be distinguished and seen to shift back and forth as the stars orbit one another.

double-star system System containing two stars in orbit around one another.

Drake equation Expression that gives an estimate of the probability that intelligence exists elsewhere in the Galaxy, based on a number of supposedly necessary conditions for intelligent life to develop. (p. 511)

dust grain An interstellar dust particle, roughly 10^{-7} m in size, comparable to the wavelength of visible light. (p. 305)

dust lane A lane of dark, obscuring interstellar dust in an emission nebula or galaxy. (p. 309)

dust tail The component of a comet's tail that is composed of dust particles. (p. 113)

dwarf Any star with radius comparable to, or smaller than, that of the Sun (including the Sun itself). (p. 289)

dwarf elliptical Elliptical galaxy as small as 1 kiloparsec across, containing only a few million stars.

dwarf galaxy Small galaxy containing a few million stars.

dwarf irregular Small irregular galaxy containing only a few million stars.

dwarf planet A body that orbits the Sun, is massive enough that its own gravity has caused its shape to be approximately spherical, but is insufficiently massive to have cleared other bodies from "the neighborhood" of its orbit. (p. 107)

dynamo theory Theory that explains planetary and stellar magnetic fields in terms of rotating, conducting material flowing in an object's interior. (p. 161)

E

E ring A faint ring, well outside the main ring system of Saturn, which was discovered by *Voyager* and is believed to be associated with volcanism on the moon Enceladus. (p. 241)

Earth-crossing asteroid An asteroid whose orbit crosses that of Earth. Earth-crossing asteroids are also called Apollo asteroids, after the first asteroid of this type discovered. (p. 108)

earthquake A sudden dislocation of rocky material near Earth's surface. (p. 149)

eccentricity A measure of the flatness of an ellipse, equal to the distance between the two foci divided by the length of the major axis. (p. 35)

eclipse Event during which one body passes in front of another, so that the light from the occulted body is blocked. (p. 14)

eclipse season Times of the year when the Moon lies in the same plane as Earth and Sun, so that eclipses are possible.

eclipse year Time interval between successive orbital configurations in which the line of nodes of the Moon's orbit points toward the Sun.

eclipsing binary Rare binary star system that is aligned in such a way that from Earth we observe one star pass in front of the other, eclipsing the other star. (p. 300)

ecliptic The apparent path of the Sun, relative to the stars on the celestial sphere, over the course of a year. (p. 10)

effective temperature Temperature of a blackbody of the same radius and luminosity as a given star or planet.

ejecta (planetary) Material thrown outward by a meteoroid impact.

ejecta (stellar) Material thrown into space by a nova or supernova.

electric field A field extending outward in all directions from a charged particle, such as a proton or an electron. The electric field determines the electric force exerted by the particle on all other charged particles in the universe; the strength of the electric field decreases with increasing distance from the charge according to an inverse-square law. (p. 48)

electromagnetic energy Energy carried in the form of rapidly fluctuating electric and magnetic fields.

electromagnetic radiation Another term for light, electromagnetic radiation transfers energy and information from one place to another. (p. 46)

electromagnetic spectrum The complete range of electromagnetic radiation, from radio waves to gamma rays, including the visible spectrum. All types of electromagnetic radiation are basically the same phenomenon, differing only by wavelength, and all move at the speed of light. (p. 50)

electromagnetism The union of electricity and magnetism, which do not exist as independent quantities but are in reality two aspects of a single physical phenomenon. (p. 49)

electron An elementary particle with a negative electric charge; one of the components of the atom. (p. 48)

electron degeneracy pressure The pressure produced by the resistance of electrons to further compression once they are squeezed to the point of contact.

electrostatic force Force between electrically charged objects.

electroweak force Unification of the weak electromagnetic forces.

element Matter made up of one particular atom. The number of protons in the nucleus of the atom determines which element it represents. (p. 63)

elementary particle Technically, a particle that cannot be subdivided into component parts; however, the term is also often used to refer to particles such as protons and neutrons, which are themselves made up of quarks.

ellipse Geometric figure resembling an elongated circle. An ellipse is characterized by its degree of flatness, or eccentricity, and the length of its long axis. In general, bound orbits of objects moving under gravity are elliptical. (p. 34)

elliptical galaxy Category of galaxy in which the stars are distributed in an elliptical shape on the sky, ranging from highly elongated to nearly circular in appearance. (p. 422)

elongation Angular distance between a planet and the Sun.

emission line Bright line in a specific location of the spectrum of radiating material, corresponding to emission of light at a certain frequency. A heated gas in a glass container produces emission lines in its spectrum. (p. 57)

emission nebula A glowing cloud of hot interstellar gas. The gas glows as a result of one or more nearby young stars that ionize the gas. Since the gas is mostly hydrogen, the emitted radiation falls predominantly in the red region of the spectrum, because of the hydrogen-alpha emission line. (p. 308)

emission spectrum The pattern of spectral emission lines produced by an element. Each element has its own unique emission spectrum. (p. 57)

empirical Discovery based on observational evidence (rather than from theory).

Encke Gap A small gap in Saturn's A ring. (p. 238)

energy flux Energy per unit area per unit time radiated by a star (or recorded by a detector).

epicycle A construct of the geocentric model of the solar system that was necessary to explain observed planetary motions. Each planet rides on a small epicycle whose center in turn rides on a larger circle (the deferent). (p. 29)

epoch of inflation Short period of unchecked cosmic expansion early in the history of the universe. During inflation, the universe swelled in size by a factor of about 10^{50}. (p. 492)

equinox *See* autumnal equinox, vernal equinox. (p. 12)

escape speed The speed necessary for one object to escape the gravitational pull of another. Anything that moves away from a gravitating body with more than the escape speed will never return. (p. 140)

euclidean geometry Geometry of flat space.

event horizon Imaginary spherical surface surrounding a collapsing star with radius equal to the Schwarzschild radius, within which no event can be seen, heard, or known about by an outside observer. (p. 374)

evolutionary theory A theory that explains observations in a series of gradual steps, explainable in terms of well-established physical principles.

evolutionary track A graphical representation of a star's life as a path on the Hertzsprung–Russell diagram. (p. 319)

excited state State of an atom when one of its electrons is in a higher energy orbital than the ground state. Atoms can become excited by absorbing a photon of a specific energy or by colliding with a nearby atom. (p. 59)

exposure time Time spent gathering light from a source. (p. 79)

extinction The dimming of starlight as it passes through the interstellar medium.

extrasolar planet Planet orbiting a star other than the Sun. (p. 119)

extremophilic Adjective describing organisms that can survive in very harsh environments. (p. 510)

eyepiece Secondary lens through which an observer views an image. This lens is often chosen to magnify the image.

F

F ring Faint narrow outer ring of Saturn, discovered by *Pioneer 11* in 1979. The F ring lies just inside the Roche limit of Saturn and was found by *Voyager 1* to be made up of several ring strands apparently braided together. (p. 240)

Fahrenheit Temperature scale in which the freezing point of water is 32 degrees and the boiling point of water is 212 degrees.

false color Representation of an image in which color does not represent true visual color, but rather an invisible wavelength of radiation, or some other property, such as temperature. (p. 87)

false vacuum Region of the universe that remained in the "unified" state after the strong and electroweak forces separated; one possible cause of cosmic inflation at very early times.

fault line Dislocation on a planet's surface, often indicating the boundary between two plates.

field line Imaginary line indicating the direction of an electric or magnetic field.

fireball Large meteor that burns up brightly and sometimes explosively in Earth's atmosphere.

firmament Old-fashioned term for the heavens (i.e., the sky).

flare Explosive event occurring in or near an active region on the Sun. (p. 267)

flatness problem One of two conceptual problems with the standard Big Bang model, which is that there is no natural way to explain why the density of the universe is so close to the critical density. (p. 492)

fluidized ejecta The ejecta blankets around some Martian craters, which apparently indicate that the ejected material was liquid at the time the crater formed.

fluorescence Phenomenon in which an atom absorbs energy, then radiates photons of lower energy as it cascades back to the ground state; in astronomy, often produced as ultraviolet photons from a hot young star that are absorbed by a neutral gas, causing some of the gas atoms to become excited and give off an optical (red) glow.

flyby Unbound trajectory of a spacecraft around a planet or other body.

focal length Distance from a mirror or the center of a lens to the focus.

focus One of two special points within an ellipse, whose separation from each other indicates the eccentricity. (p. 34)

In a bound orbit, planets orbit in ellipses with the Sun at one focus. (p. 34)

forbidden line A spectral line seen in emission nebulae, but not seen in laboratory experiments because, under laboratory conditions, collisions kick the electron in question into some other state before emission can occur.

force Action on an object that causes its momentum to change. The rate at which the momentum changes is numerically equal to the force. (p. 37)

fragmentation The breaking up of a large object into many smaller pieces (for example, as the result of high-speed collisions between planetesimals and protoplanets in the early solar system). (p. 124)

Fraunhofer lines The collection of over 600 absorption lines in the spectrum of the Sun, first categorized by Joseph Fraunhofer in 1812.

frequency The number of wave crests passing any given point per unit time. (p. 47)

full When the full hemisphere of the Moon or a planet can be seen from Earth.

full Moon Phase of the Moon in which it appears as a complete circular disk in the sky. (p. 14)

fusion *See* nuclear fusion.

G

G ring Faint, narrow ring of Saturn, discovered by *Pioneer 11* and lying just outside the F ring.

galactic bulge Thick distribution of warm gas and stars around the galactic center. (p. 392)

galactic cannibalism A galaxy merger in which a larger galaxy consumes a smaller one.

galactic center The center of the Milky Way, or any other galaxy. The point about which the disk of a spiral galaxy rotates. (p. 396)

galactic disk An immense, circular, flattened region containing most of a galaxy's luminous stars and interstellar matter. (p. 392)

galactic epoch Period from 100 million to 3 billion years after the Big Bang when large agglomerations of matter (galaxies and galaxy clusters) formed and grew.

galactic habitable zone Region of a galaxy in which conditions are conducive to the development of life.

galactic halo Region of a galaxy extending far above and below the galactic disk, where globular clusters and other old stars reside. (p. 392)

galactic nucleus Small, central, high-density region of a galaxy. Many galactic nuclei are thought to contain supermassive black holes, and almost all the radiation from active galaxies is generated within the nucleus. (pp. 410, 419)

galactic rotation curve Plot of rotation speed versus distance from the center of a galaxy.

galactic year Time taken for objects at the distance of the Sun (about 8 kpc) to orbit the center of the Galaxy, roughly 225 million years.

galaxy Gravitationally bound collection of a large number of stars. The Sun is a star in the Milky Way Galaxy. (pp. 6, 392)

galaxy cluster A collection of galaxies held together by their mutual gravitational attraction. (p. 429)

Galilean moons The four large moons of Jupiter discovered by Galileo Galilei.

Galilean satellites The four brightest and largest moons of Jupiter (Io, Europa, Ganymede, Callisto), named after Galileo Galilei, the 17th-century astronomer who first observed them.

gamma ray Region of the electromagnetic spectrum, far beyond the visible spectrum, corresponding to radiation of very high frequency and very short wavelength. (p. 46)

gamma-ray burst Object that radiates tremendous amounts of energy in the form of gamma rays, possibly due to the collision and merger of two neutron stars initially in orbit around one another. (p. 368)

gamma-ray spectrograph Spectrograph designed to work at gamma-ray wavelengths. Used to map the abundances of certain elements on the Moon and Mars.

gaseous Composed of gas.

gas-exchange experiment Experiment to look for life on Mars. A nutrient broth was offered to Martian soil specimens. If there were life in the soil, gases would be created as the broth was digested.

gene Sequence of nucleotide bases in the DNA molecule that determines the characteristics of a living organism.

general theory of relativity Theory proposed by Einstein to incorporate gravity into the framework of special relativity (p. 373).

geocentric model A model of the solar system that holds that Earth is at the center of the universe and all other bodies are in orbit around it. The earliest theories of the solar system were geocentric. (p. 29)

giant A star with a radius between 10 and 100 times that of the Sun. (p. 289)

giant elliptical Elliptical galaxy up to a few megaparsecs across, containing trillions of stars.

gibbous Appearance of the Moon (or a planet) when more than half (but not all) of the body's hemisphere is visible from Earth.

globular cluster Tightly bound, roughly spherical collection of hundreds of thousands, and sometimes millions, of stars spanning about 50 parsecs. Globular clusters are distributed in the halos around the Milky Way and other galaxies. (p. 324)

gluon Particle that exerts or mediates the strong force in quantum physics.

gradient Rate of change of some quantity (e.g., temperature or composition) with respect to location in space.

Grand Unified Theories Class of theories describing the behavior of the single force that results from unification of the strong, weak, and electromagnetic forces in the early universe. (p. 492)

granite Igneous rock, containing silicon and aluminum, that makes up most of Earth's crust.

granulation Mottled appearance of the solar surface, caused by rising (hot) and falling (cool) material in convective cells just below the photosphere. (p. 259)

gravitational force Force exerted on one body by another due to the effect of gravity. The force is directly proportional to the masses of both bodies involved and inversely proportional to the square of the distance between them. (p. 38)

gravitational instability theory Theory that the jovian planets formed directly from the solar nebula via instabilities in the gas leading to gravitational contraction. *See* core-accretion theory.

gravitational lensing The effect induced on the image of a distant object by a massive foreground object. Light from the distant object is bent into two or more separate images. (p. 407)

gravitational radiation Radiation resulting from rapid changes in a body's gravitational field.

gravitational redshift A prediction of Einstein's general theory of relativity. Photons lose energy as they escape the gravitational field of a massive object. Because a photon's energy is proportional to its frequency, a photon that loses energy suffers a decrease in frequency, which corresponds to an increase, or redshift, in wavelength. (p. 381)

graviton Particle carrying the gravitational field in theories attempting to unify gravity and quantum mechanics.

gravity The attractive effect that any massive object has on all other massive objects. The greater the mass of the object, the stronger its gravitational pull. (p. 38)

gravity assist Using gravity to change the flight path of a satellite or spacecraft.

gravity wave Gravitational counterpart of an electromagnetic wave.

great attractor A huge accumulation of mass in the relatively nearby universe (within about 200 Mpc of the Milky Way).

Great Dark Spot Prominent storm system in the atmosphere of Neptune observed by *Voyager 2*, near the equator of the planet. The system was comparable in size to Earth. (p. 215)

Great Red Spot A large, high-pressure, long-lived storm system visible in the atmosphere of Jupiter. The Red Spot is roughly twice the size of Earth. (p. 215)

great wall Extended sheet of galaxies measuring at least 200 megaparsecs across; one of the largest known structures in the universe.

greenhouse effect The partial trapping of solar radiation by a planetary atmo-sphere, similar to the trapping of heat in a greenhouse. (p. 147)

greenhouse gas Gas (such as carbon dioxide or water vapor) that efficiently absorbs infrared radiation.

ground state The lowest energy state that an electron can have within an atom. (p. 60)

GUT epoch Period when gravity separated from the other three forces of nature.

gyroscope System of rotating wheels that allows a spacecraft to maintain a fixed orientation in space.

H

habitable zone Three-dimensional zone of comfortable temperature (corresponding to liquid water) that surrounds every star. (p. 133)

half-life The amount of time it takes for half of the initial amount of a radioactive substance to decay into something else.

Hayashi track Evolutionary track followed by a protostar during the final premain-sequence phase before nuclear fusion begins.

heat Thermal energy, the energy of an object due to the random motion of its component atoms or molecules.

heat death End point of a bound universe, in which all matter and life are destined to be incinerated.

heavy element In astronomical terms, any element heavier than hydrogen and helium.

heliocentric model A model of the solar system that is centered on the Sun, with Earth in motion about the Sun. (p. 31)

helioseismology The study of conditions far below the Sun's surface through the analysis of internal "sound" waves that repeatedly cross the solar interior. (p. 250)

helium-burning shell Shell of burning helium gas surrounding a nonburning stellar core of carbon ash.

helium capture The formation of heavy elements by the capture of a helium nucleus. For example, carbon can form heavier elements by fusion with other carbon nuclei, but it is much more likely to occur by helium capture, which requires less energy.

helium flash An explosive event in the post-main-sequence evolution of a low-mass star. When helium fusion begins in a dense stellar core, the burning is explosive in nature. It continues until the energy released is enough to expand the core, at which point the star achieves stable equilibrium again. (p. 335)

helium precipitation Mechanism responsible for the low abundance of helium of Saturn's atmosphere. Helium condenses in the upper layers to form a mist that rains down toward Saturn's interior, just as water vapor forms into rain in the atmosphere of Earth.

helium shell flash Condition in which the helium-burning shell in the core of a star cannot respond to rapidly changing conditions within it, leading to a sudden temperature rise and a dramatic increase in nuclear reaction rates.

Hertzsprung–Russell (H–R) diagram A plot of luminosity against temperature (or spectral class) for a group of stars. (p. 289)

hierarchical merging Widely accepted galaxy-formation scenario in which galaxies formed as relatively small objects in the early universe and subsequently collided and merged to form the large galaxies observed today. The present Hubble type of a galaxy depends on the sequence of merger events in the galaxy's past. (p. 453)

high-energy astronomy Astronomy using X- or gamma-ray radiation rather than optical radiation.

high-energy telescope Telescope designed to detect X- and gamma-ray radiation. (p. 94)

highlands Relatively light-colored regions on the surface of the Moon that are elevated several kilometers above the maria. Also called terrae. (p. 155)

high-mass star Star with a mass more than 8 times that of the Sun; progenitor of a neutron star or black hole.

HI region Region of space containing primarily neutral hydrogen.

HII region Region of space containing primarily ionized hydrogen.

homogeneity Assumed property of the universe such that the number of galaxies in an imaginary large cube of the universe is the same no matter where in the universe the cube is placed. (p. 477)

horizon problem One of two conceptual problems with the standard Big Bang model, which is that some regions of the universe that have very similar properties are too far apart to have exchanged information within the age of the universe. (p. 491)

horizontal branch Region of the Hertzsprung–Russell diagram where post-main-sequence stars again reach hydrostatic equilibrium. At this point, the star is burning helium in its core and fusing hydrogen in a shell surrounding the core. (p. 335)

hot dark matter A class of candidates for the dark matter in the universe, composed of lightweight particles such as neutrinos, much less massive than the electron.

hot Jupiter A massive, gaseous planet orbiting very close to its parent star. (p. 130)

hot longitudes (Mercury) Two opposite points on Mercury's equator where the Sun is directly overhead at perihelion.

Hubble classification scheme Method of classifying galaxies according to their appearance, developed by Edwin Hubble. (p. 420)

Hubble diagram Plot of galactic recession velocity versus distance; evidence for an expanding universe.

Hubble flow Universal recession described by the Hubble diagram and quantified by Hubble's law.

Hubble sequence Hubble's arrangement of elliptical, S0, and spiral galaxies, often used to classify galaxies but not thought to represent a true evolutionary sequence in any sense. (p. 424)

Hubble's constant The constant of proportionality that gives the relation between recessional velocity and distance in Hubble's law. (p. 431)

Hubble's law Law that relates the observed velocity of recession of a galaxy to its distance from us. The velocity of recession of a galaxy is directly proportional to its distance away. (p. 430)

hydrocarbon Molecules consisting solely of hydrogen and carbon.

hydrogen envelope An invisible sheath of gas engulfing the coma of a comet, usually distorted by the solar wind and extending across millions of kilometers of space. (p. 112)

hydrogen shell burning Fusion of hydrogen in a shell that is driven by contraction and heating of the helium core. Once hydrogen is depleted in the core of a star, hydrogen burning stops and the core contracts due to gravity, causing the temperature to rise, heating the surrounding layers of hydrogen in the star, and increasing the burning rate there. (p. 334)

hydrosphere Layer of Earth that contains the liquid oceans and accounts for roughly 70 percent of Earth's total surface area. (p. 140)

hydrostatic equilibrium Condition in a star or other fluid body in which gravity's inward pull is exactly balanced by internal forces due to pressure. (p. 255)

hyperbola Curve formed when a plane intersects a cone at a small angle to the axis of the cone.

hypernova Explosion where a massive star undergoes core collapse and forms a black hole and a gamma-ray burst. *See* supernova.

I

igneous Rocks formed from molten material.

image The optical representation of an object produced when the object is reflected or refracted by a mirror or lens. (p. 72)

impact theory (Moon) Combination of the capture and daughter theories, suggesting that the Moon formed after an impact that dislodged some of Earth's mantle and placed it in orbit.

inertia The tendency of an object to continue moving at the same speed and in the same direction, unless acted upon by a force. (p. 38)

inferior conjunction Orbital configuration in which an inferior planet (Mercury or Venus) lies closest to Earth.

inflation *See* epoch of inflation.

infrared Region of the electromagnetic spectrum just outside the visible range, corresponding to light of a slightly longer wavelength than red light. (p. 46)

infrared telescope Telescope designed to detect infrared radiation. Many such telescopes are designed to be lightweight so that they can be carried above (most of) Earth's atmosphere by balloons, airplanes, or satellites. (p. 90)

infrared waves Electromagnetic radiation with wavelength in the infrared part of the spectrum. (p. 46)

inhomogeneity Deviation from perfectly uniform density; in cosmology, inhomogeneities in the universe are ultimately due to quantum fluctuations before inflation.

inner core The central part of Earth's core, believed to be solid and composed mainly of nickel and iron. (p. 150)

instability strip Part of the Hertzsprung–Russell diagram where pulsating post-main-sequence stars are found.

intensity A basic property of electromagnetic radiation that specifies the amount or strength of the radiation. (p. 51)

intercloud medium Superheated bubbles of hot gas extending far into interstellar space.

intercrater plains Regions on the surface of Mercury that do not show extensive cratering but are relatively smooth. (p. 175)

interference The ability of two or more waves to interact in such a way that they either reinforce or cancel each other. (p. 48)

interferometer Collection of two or more telescopes working together as a team, observing the same object at the same time and at the same wavelength. The effective diameter of an interferometer is equal to the distance between its outermost telescopes. (p. 88)

interferometry Technique in widespread use to dramatically improve the resolution of radio and infrared maps. Several telescopes observe the object simultaneously, and a computer analyzes how the signals interfere with each other. (p. 88)

intermediate-mass black hole Black hole having a mass 100–1000 times greater than the mass of the Sun.

interplanetary matter Matter in the solar system that is not part of a planet or moon—cosmic "debris."

interstellar dust Microscopic dust grains that populate space between the stars, having their origins in the ejected matter of long-dead stars.

interstellar gas cloud A large cloud of gas found in the space among the stars.

interstellar medium The matter between stars, composed of two components, gas and dust, intermixed throughout all of space. (p. 304)

intrinsic variable Star that varies in appearance due to internal processes (rather than, say, interaction with another star).

inverse-square law The law that a field follows if its strength decreases with the square of the distance. Fields that follow the inverse-square law decrease rapidly in strength as the distance increases, but never quite reach zero. (p. 39)

Io plasma torus Doughnut-shaped region of energetic ionized particles emitted by the volcanoes on Jupiter's moon Io and swept up by Jupiter's magnetic field.

ion An atom that has lost one or more of its electrons. (p. 60)

ionization state Term describing the number of electrons missing from an atom: I refers to a neutral atom, II refers to an atom missing one electron, and so on.

ionosphere Layer in Earth's atmosphere above about 100 km where the atmosphere is significantly ionized and conducts electricity. (p. 144)

ion tail Thin stream of ionized gas that is pushed away from the head of a comet by the solar wind. It extends directly away from the Sun. Often referred to as a plasma tail. (p. 113)

irregular galaxy A galaxy that does not fit into any of the other major categories in the Hubble classification scheme. (p. 424)

isotopes Nuclei containing the same number of protons but different numbers of neutrons. Most elements can exist in several isotopic forms. A common example of an isotope is deuterium, which differs from normal hydrogen by the presence of an extra neutron in the nucleus.

isotropic Assumed property of the universe such that the universe looks the same in every direction. (p. 478)

J

jet stream Relatively strong winds in the upper atmosphere channeled into a narrow stream by a planet's rotation. Normally refers to a horizontal, high-altitude wind.

joule The SI unit of energy.

jovian planet One of the four giant outer planets of the solar system, resembling Jupiter in physical and chemical composition. (p. 108)

K

Kelvin scale Temperature scale in which absolute zero is at 0 K; a change of 1 kelvin is the same as a change of 1 degree Celsius.

Kelvin-Helmholtz contraction phase Evolutionary track followed by a star during the protostar phase.

Kepler's laws of planetary motion Three laws, based on precise observations of the motions of the planets by Tycho Brahe that summarize the motions of the planets about the Sun.

kinetic energy Energy of an object due to its motion.

Kirchhoff's laws Three rules governing the formation of different types of spectra. (p. 59)

Kirkwood gaps Gaps in the spacings of orbital semimajor axes of asteroids in the asteroid belt, produced by dynamical resonances with nearby planets, especially Jupiter.

Kuiper belt A region in the plane of the solar system outside the orbit of Neptune where most short-period comets are thought to originate. (p. 115)

Kuiper belt object Small icy body orbiting in the Kuiper belt. (p. 112)

L

labeled-release experiment Experiment to look for life on Mars. Radioactive carbon compounds were added to Martian soil specimens. Scientists looked for indications that the carbon had been eaten or inhaled.

Lagrangian point One of five special points in the plane of two massive bodies orbiting one another, where a third body of negligible mass can remain in equilibrium.

lander Spacecraft that lands on the object it is studying.

laser ranging Method of determining the distance to an object by firing a laser beam at it and measuring the time taken for the light to return.

lava dome Volcanic formation formed when lava oozes out of fissures in a planet's surface, creating the dome, and then withdraws, causing the crust to crack and subside.

law of conservation of mass and energy A fundamental law of modern physics that states that the sum of mass and energy must always remain constant in any physical process. In fusion reactions, the lost mass is converted into energy, primarily in the form of electromagnetic radiation. (p. 270)

laws of planetary motion Three laws derived by Kepler describing the motion of the planets around the Sun. (p. 34)

leap year Year in which an additional day is inserted into the calendar in order to keep the calendar year synchronized with Earth's orbit around the Sun.

lens Optical instrument made of glass or some other transparent material, shaped so that, as a parallel beam of light passes through it, the rays are refracted so as to pass through a single focal point.

lens (eye) The part of the eye that refracts light onto the retina.

lepton Greek word for light, referring in particle physics to low-mass particles such as electrons, muons, and neutrinos that interact via the weak force.

lepton epoch Period when the light elementary particles (leptons) were in thermal equilibrium with the cosmic radiation field.

lidar Light Detection and Ranging—a device that uses laser-ranging to measure distance.

light *See* electromagnetic radiation.

light curve The variation in brightness of a star with time. (p. 295)

light element In astronomical terms, hydrogen and helium.

light-gathering power Amount of light a telescope can view and focus, proportional to the area of the primary mirror.

lighthouse model The leading explanation for pulsars. A small region of the neutron star, near one of the magnetic poles, emits a steady stream of radiation that sweeps past Earth each time the star rotates. The period of the pulses is the star's rotation period. (p. 364)

light-year The distance that light, moving at a constant speed of 300,000 km/s, travels in 1 year. One light-year is about 10 trillion kilometers.

limb Edge of a lunar, planetary, or solar disk.

linear momentum Tendency of an object to keep moving in a straight line with constant velocity; the product of the object's mass and velocity.

line of nodes Intersection of the plane of the Moon's orbit with Earth's orbital plane.

line of sight technique Method of probing interstellar clouds by observing their effects on the spectra of background stars.

lithosphere Earth's crust and a small portion of the upper mantle that make up Earth's plates. This layer of Earth undergoes tectonic activity.

Local Bubble The particular low-density intercloud region surrounding the Sun.

Local Group The small galaxy cluster that includes the Milky Way Galaxy. (p. 428)

local supercluster Collection of galaxies and clusters centered on the Virgo cluster. *See also* supercluster.

logarithm The power to which 10 must be raised to produce a given number.

logarithmic scale Scale using the logarithm of a number rather than the number itself; commonly used to compress a large range of data into more manageable form.

look-back time Time in the past when an object emitted the radiation we see today.

low-mass star Star with a mass less than 8 times that of the Sun; progenitor of a white dwarf.

luminosity One of the basic properties used to characterize stars, luminosity is defined as the total energy radiated by a star each second, at all wavelengths. (p. 255)

luminosity class A classification scheme that groups stars according to the width of their spectral lines. For a group of stars with the same temperature, luminosity class differentiates between supergiants, giants, main-sequence stars, and subdwarfs. (p. 294)

lunar dust *See* regolith.

lunar eclipse Celestial event during which the moon passes through the shadow of Earth, temporarily darkening its surface. (p. 14)

lunar phase The appearance of the Moon at different points along its orbit.

Lyman-alpha forest Collection of lines in an object's spectra starting at the redshifted wavelength of the object's own Lyman-alpha emission line and extending to shorter wavelengths; produced by gas in galaxies along the line of sight.

M

macroscopic Large enough to be visible by the unaided eye.

Magellanic Clouds Two small irregular galaxies that are gravitationally bound to the Milky Way Galaxy. (p. 424)

magnetic field Field that accompanies any changing electric field and governs the influence of magnetized objects on one another. (p. 49)

magnetic poles Points on a planet where the planetary magnetic field lines intersect the planet's surface vertically.

magnetism The presence of a magnetic field.

magnetometer Instrument that measures magnetic field strength.

magnetopause Boundary between a planet's magnetosphere and the solar wind.

magnetosphere A zone of charged particles trapped by a planet's magnetic field, lying above the atmosphere. (p. 140)

magnitude scale A system of ranking stars by apparent brightness, developed by the Greek astronomer Hipparchus. Originally, the brightest stars in the sky were categorized as being of first magnitude, while the faintest stars visible to the naked eye were classified as sixth magnitude. The scheme has since been extended to cover stars and galaxies too faint to be seen by the unaided eye. Increasing magnitude means fainter stars, and a difference of five magnitudes corresponds to a factor of 100 in apparent brightness. (p. 284)

main sequence Well-defined band on the Hertzsprung–Russell diagram on which most stars are found, running from the top left of the diagram to the bottom right. (p. 290)

main-sequence turnoff Special point on the Hertzsprung–Russell diagram for a cluster, indicative of the cluster's age. If all the stars in the cluster are plotted, the lower-mass stars will trace out the main sequence up to the point where stars begin to evolve off the main sequence toward the red giant branch. The point where stars are just beginning to evolve off is the main-sequence turnoff. (p. 351)

major axis The long axis of an ellipse.

mantle Layer of Earth just interior to the crust. (p. 140)

marginally bound universe Universe that will expand forever but at an increasingly slow rate.

maria Relatively dark-colored and smooth regions on the surface of the Moon (singular: *mare*). (p. 155)

mass A measure of the total amount of matter contained within an object. (p. 38)

mass function Relation between the component masses of a single-line spectroscopic binary.

massive compact halo object (MACHO) Collective name for "stellar" candidates for dark matter, including brown dwarfs, white dwarfs, and low-mass red dwarfs.

mass–luminosity relation The dependence of the luminosity of a main-sequence star on its mass. The luminosity increases roughly as the mass raised to the third power.

mass–radius relation The dependence of the radius of a main-sequence star on its mass. The radius rises roughly in proportion to the mass.

mass transfer Process by which one star in a binary system transfers matter onto the other.

mass-transfer binary *See* semidetached binary.

matter Anything having mass.

matter–antimatter annihilation Reaction in which matter and antimatter annihilate to produce high energy gamma rays. *See also* antiparticle.

matter-dominated universe A universe in which the density of matter exceeds the density of radiation. The present-day universe is matter dominated.

matter era (Current) era following the radiation era when the universe is larger and cooler and matter is the dominant constituent of the universe.

Maunder minimum Lengthy period of solar inactivity that extended from 1645 to 1715.

mean solar day Average length of time from one noon to the next, taken over the course of a year—24 hours.

medium Material through which a wave, such as sound, travels.

meridian An imaginary line on the celestial sphere through the north and south celestial poles, passing directly overhead at a given location.

mesosphere Region of Earth's atmosphere lying between the stratosphere and the ionosphere, 50–80 km above Earth's surface. (p. 144)

Messier object Member of a list of "fuzzy" objects compiled by astronomer Charles Messier in the 18th century.

metabolism The daily utilization of food and energy by which organisms stay alive.

metallic Composed of metal or metal compounds.

metamorphic Rocks created from existing rocks exposed to extremes of temperature or pressure.

meteor Bright streak in the sky, often referred to as a "shooting star," resulting from a small piece of interplanetary debris entering Earth's atmosphere and heating air molecules, which emit light as they return to their ground states. (p. 115)

meteorite Any part of a meteoroid that survives passage through the atmosphere and lands on the surface of Earth. (p. 116)

meteoroid Chunk of interplanetary debris prior to encountering Earth's atmo-sphere. (p. 107)

meteoroid swarm Pebble-sized cometary fragments dislodged from the main body, moving in nearly the same orbit as the parent comet. (p. 116)

meteor shower Event during which many meteors can be seen each hour, caused by the yearly passage of Earth through the debris spread along the orbit of a comet.

microlensing Gravitational lensing by individual stars in a galaxy.

micrometeoroid Relatively small chunks of interplanetary debris ranging from dust-particle size to pebble-sized fragments. (p. 116)

microsphere Small droplet of protein-like material that resists dissolution in water.

midocean ridge Place where two plates are moving apart, allowing fresh magma to well up.

Milky Way Galaxy The spiral galaxy in which the Sun resides. The disk of our Galaxy is visible in the night sky as the faint band of light known as the Milky Way. (p. 392)

millisecond pulsar A pulsar whose period indicates that the neutron star is rotating nearly 1000 times each second. The most likely explanation for these rapid rotators is that the neutron star has been spun up by drawing in matter from a companion star. (p. 366)

molecular cloud A cold, dense interstellar cloud that contains a high fraction of molecules. It is widely believed that the relatively high density of dust particles in these clouds plays an important role in the formation and preservation of the molecules. (p. 314)

molecular cloud complex Collection of molecular clouds that spans as much as 50 parsecs and may contain enough material to make millions of Sun-size stars. (p. 314)

molecule A tightly bound collection of atoms held together by the atoms' electromagnetic fields. Molecules, like atoms, emit and absorb photons at specific wavelengths. (p. 62)

molten In liquid form due to high temperatures.

moon A small body in orbit around a planet.

mosaic (photograph) Composite photograph made up of many smaller images.

M-type asteroid Asteroid containing large fractions of nickel and iron.

multiple star system Group of two or more stars in orbit around one another.

muon A type of lepton (along with the electron and tau).

N

naked singularity A singularity that is not hidden behind an event horizon.

nanobacterium Very small bacterium with diameter in the nanometer range.

nanometer One billionth of a meter.

neap tide The smallest tides, occurring when the Earth–Moon line is perpendicular to the Earth–Sun line at the first and third quarters.

nebula General term used for any "fuzzy" patch on the sky, either light or dark. (pp. 121, 306)

nebular theory One of the earliest models of solar system formation, dating back to Descartes, in which a large cloud of gas began to collapse under its own gravity to form the Sun and planets. (p. 121)

nebulosity "Fuzziness," usually in the context of an extended or gaseous astronomical object.

neon–oxygen white dwarf White dwarf formed from a low-mass star with a mass close to the "high-mass" limit, in which neon and oxygen form in the core.

neutrino Virtually massless and chargeless particle that is one of the products of fusion reactions in the Sun. Neutrinos move at close to the speed of light and interact with matter hardly at all. (p. 274)

neutrino oscillations Possible solution to the solar neutrino problem, in which the neutrino has a very tiny mass. In this case, the correct number of neutrinos can be produced in the solar core, but on their way to Earth some can "oscillate," or become transformed into other particles, and thus go undetected. (p. 274)

neutron An elementary particle with roughly the same mass as a proton, but which is electrically neutral. Along with protons, neutrons form the nuclei of atoms. (p. 63)

neutron capture The primary mechanism by which very massive nuclei are formed in the violent aftermath of a supernova. Instead of fusion of like nuclei, heavy elements are created by the addition of more and more neutrons to existing nuclei.

neutron degeneracy pressure Pressure due to the Pauli exclusion principle, arising when neutrons are forced to come into close contact.

neutronization Process occurring at high densities, in which protons and electrons are crushed together to form neutrons and neutrinos.

neutron spectrometer Instrument designed to search for water ice by looking for hydrogen.

neutron star A dense ball of neutrons that remains at the core of a star after a supernova explosion has destroyed the rest of the star. Typical neutron stars are about 20 km across and contain more mass than the Sun. (p. 362)

new Moon Phase of the moon during which none of the lunar disk is visible. (p. 14)

Newtonian mechanics The basic laws of motion postulated by Newton, which are sufficient to explain and quantify virtually all of the complex dynamical behavior found on Earth and elsewhere in the universe. (p. 37)

Newtonian telescope A reflecting telescope in which incoming light is intercepted before it reaches the prime focus and is deflected into an eyepiece at the side of the instrument. (p. 74)

nodes Two points on the Moon's orbit when it crosses the ecliptic.

nonrelativistic Speeds that are much less than the speed of light.

nonthermal spectrum Continuous spectrum not well described by a blackbody.

north celestial pole Point on the celestial sphere directly above Earth's North Pole. (p. 8)

Northern and Southern Lights Colorful displays produced when atmospheric molecules, excited by charged particles from the Van Allen belts, fall back to their ground state.

nova A star that suddenly increases in brightness, often by a factor of as much as 10,000, then slowly fades back to its original luminosity. A nova is the result of an explosion on the surface of a white-dwarf star, caused by matter falling onto its surface from the atmosphere of a binary companion. (p. 340)

nuclear binding energy Energy that must be supplied to split an atomic nucleus into neutrons and protons.

nuclear epoch Period when protons and neutrons fused to form heavier nuclei.

nuclear fusion Mechanism of energy generation in the core of the Sun, in which light nuclei are combined, or fused, into heavier ones, releasing energy in the process. (p. 270)

nuclear reaction Reaction in which two nuclei combine to form other nuclei, often releasing energy in the process. *See also* fusion.

nucleotide base An organic molecule, the building block of genes that pass on hereditary characteristics from one generation of living creatures to the next. (p. 505)

nucleus Dense, central region of an atom containing both protons and neutrons and orbited by one or more electrons. (p. 60)

The solid region of ice and dust that composes the central region of the head of a comet. (p. 112)

The dense central core of a galaxy. (p. 433)

O

obscuration Blockage of light by pockets of interstellar dust and gas.

Olbers's paradox A thought experiment suggesting that if the universe were homogeneous, infinite, and unchanging, the entire night sky would be as bright as the surface of the Sun. (p. 477)

Oort cloud Spherical halo of material surrounding the solar system out to a distance of about 50,000 AU; where most comets reside. (p. 115)

opacity A quantity that measures a material's ability to block electromagnetic radiation. Opacity is the opposite of transparency. (p. 52)

open cluster Loosely bound collection of tens to hundreds of stars, a few parsecs across, generally found in the plane of the Milky Way. (p. 324)

open universe Geometry that the universe would have if the density of matter were less than the critical value. In an open universe there is not enough matter to halt the expansion of the universe. An open universe is infinite in extent. (p. 482)

opposition Orbital configuration in which a planet lies in the opposite direction from the Sun, as seen from Earth.

optical double Chance superposition in which two stars appear to lie close together but are actually widely separated.

optical telescope Telescope designed to observe electromagnetic radiation at optical wavelengths.

orbital One of several energy states in which an electron can exist in an atom.

orbital period Time taken for a body to complete one full orbit around another.

orbiter Spacecraft that orbits an object to make observations.

organic compound Chemical compound (molecule) containing a significant fraction of carbon atoms; the basis of living organisms.

outer core The outermost part of Earth's core, believed to be liquid and composed mainly of nickel and iron. (p. 150)

outflow channel Surface feature on Mars, evidence that liquid water once existed there in great quantity; believed to be the relics of catastrophic flooding about 3 billion years ago. Found only in the equatorial regions of the planet. (p. 184)

outgassing Production of atmospheric gases (carbon dioxide, water vapor, methane, and sulphur dioxide) by volcanic activity.

ozone layer Layer of Earth's atmosphere at an altitude of 20–50 km where incoming ultraviolet solar radiation is absorbed by oxygen, ozone, and nitrogen in the atmosphere. (p. 145)

P

parallax The apparent motion of a relatively close object with respect to a more distant background as the location of the observer changes. (p. 19)

parsec The distance at which a star must lie in order for its measured parallax to be exactly 1 arc second; 1 parsec equals 206,000 AU. (p. 280)

partial eclipse Celestial event during which only a part of the occulted body is blocked from view. (p. 16)

particle A body with mass but of negligible dimension.

particle accelerator Device used to accelerate subatomic particles to relativistic speeds.

particle–antiparticle pair Pair of particles (e.g., an electron and a positron) produced by two photons of sufficiently high energy.

particle detector Experimental equipment that allows particles and antiparticles to be detected and identified.

Pauli exclusion principle A rule of quantum mechanics that prohibits electrons in dense gas from being squeezed too closely together.

penumbra Portion of the shadow cast by an eclipsing object in which the eclipse is seen as partial. (p. 15)

The outer region of a sunspot, surrounding the umbra, which is not as dark and not as cool as the central region. (p. 254)

perihelion The closest approach to the Sun of any object in orbit about it. (p. 35)

period The time needed for an orbiting body to complete one revolution about another body. (p. 35)

period–luminosity relation A relation between the pulsation period of a Cepheid variable and its absolute brightness. Measurement of the pulsation period allows the distance of the star to be determined. (p. 395)

permafrost Layer of permanently frozen water ice believed to lie just under the surface of Mars. (p. 185)

phase Appearance of the sunlit face of the Moon at different points along its orbit, as seen from Earth. (p. 14)

photodisintegration Process occurring at high temperatures, in which individual photons have enough energy to split a heavy nucleus (e.g., iron) into lighter nuclei.

photoelectric effect Emission of an electron from a surface when a photon of electromagnetic radiation is absorbed.

photoevaporation Process in which a cloud in the vicinity of a newborn hot star is dispersed by the star's radiation.

photometer A device that measures the total amount of light received in all or part of the image.

photometry Branch of observational astronomy in which the brightness of a source is measured through each of a set of standard filters.

photomicrograph Photograph taken through a microscope.

photon Individual packet of electromagnetic energy that makes up electromagnetic radiation. (p. 61)

photosphere The visible surface of the Sun, lying just above the uppermost layer of the Sun's interior and just below the chromosphere. (p. 254)

photosynthesis Process by which plants manufacture carbohydrates and oxygen from carbon dioxide and water, using chlorophyll and sunlight as the energy source.

pixel One of many tiny picture elements, organized into an array, making up a digital image.

Planck curve *See* blackbody curve.

Planck epoch Period from the beginning of the universe to roughly 10^{-43} second, when the laws of physics are not understood.

Planck's constant Fundamental physical constant relating the energy of a photon to its radiation frequency (color).

planet One of eight major bodies that orbit the Sun, visible to us by reflected sunlight. (p. 6)

planetary nebula The ejected envelope of a red-giant star, spread over a volume roughly the size of our solar system. (p. 335)

planetary ring system Material organized into thin, flat rings encircling a giant planet, such as Saturn.

planetesimal Term given to objects in the early solar system that had reached the size of small moons, at which point their gravitational fields were strong enough to begin influencing their neighbors. (p. 123)

plasma A gas in which the constituent atoms are completely ionized.

plate tectonics The motions of regions of Earth's lithosphere, which drift with respect to one another. Also known as continental drift. (p. 152)

plutino Kuiper belt object whose orbital period (like that of Pluto) is in a 3:2 resonance with the orbit of Neptune.

plutoid A dwarf planet orbiting beyond Neptune. (p. 246)

polarity A measure of the direction of the solar magnetic field in a sunspot. Conventionally, lines coming out of the surface are labeled "S," while those going into the surface are labeled "N." (p. 264)

polarization The alignment of the electric fields of emitted photons, which are generally emitted with random orientations.

Population I and II stars Classification scheme for stars based on the abundance of heavy elements. Within the Milky Way, Population I refers to young disk stars, and Population II refers to old halo stars.

positron Atomic particle with properties identical to those of a negatively charged electron, except for its positive charge. This positron is the antiparticle of the electron. Positrons and electrons annihilate one another when they meet, producing pure energy in the form of gamma rays. (p. 271)

prebiotic compound Molecule that can combine with others to form the building blocks of life.

precession The slow change in the direction of the rotation axis of a spinning object, caused by some external gravitational influence. (p. 12)

primary mirror Mirror placed at the prime focus of a telescope. *See* prime focus.

prime focus The point in a reflecting telescope where the mirror focuses incoming light to a point. (p. 72)

prime-focus image Image formed at the prime focus of a telescope.

primeval fireball Hot, dense state of the universe at very early times, just after the Big Bang. (p. 478)

primordial matter Matter created during the early, hot epochs of the universe.

primordial nucleosynthesis The production of elements heavier than hydrogen by nuclear fusion in the high temperatures and densities that existed in the early universe. (p. 489)

principle of cosmic censorship A proposition to separate the unexplained physics near a singularity from the rest of the well-behaved universe. The principle states that nature always hides any singularity, such as a black hole, inside an event horizon, which insulates the rest of the universe from seeing it.

progenitor "Ancestor" star of a given object; for example, the star that existed before a supernova explosion is the supernova's progenitor.

prograde motion Motion across the sky in the eastward direction.

prominence Loop or sheet of glowing gas ejected from an active region on the solar surface that then moves through the inner parts of the corona under the influence of the Sun's magnetic field. (p. 267)

proper motion The angular movement of a star across the sky, as seen from Earth, measured in seconds of arc per year. This movement is a result of the star's actual motion through space. (p. 282)

protein Molecule made up of amino acids that controls metabolism.

proton An elementary particle carrying a positive electric charge, a component of all atomic nuclei. The number of protons in the nucleus of an atom dictates what type of atom it is. (p. 48)

proton–proton chain The chain of fusion reactions, leading from hydrogen to helium, that powers main-sequence stars. (p. 271)

protoplanet Clump of material, formed in the early stages of solar system formation, that was the forerunner of the planets we see today. (p. 123)

protostar Stage in star formation when the interior of a collapsing fragment of gas is sufficiently hot and dense that it becomes opaque to its own radiation. The protostar is the dense region at the center of the fragment. (p. 316)

protosun The central accumulation of material in the early stages of solar system formations, the forerunner of the present-day Sun. (p. 124)

Ptolemaic model Geocentric solar system model, developed by the second century astronomer Claudius Ptolemy. It predicted with great accuracy the positions of the then known planets. (p. 29)

pulsar Object that emits radiation in the form of rapid pulses with a characteristic pulse period and duration. Charged particles, accelerated by the magnetic field of a rapidly rotating neutron star, flow along the magnetic field lines, producing radiation that beams outward as the star spins on its axis. (p. 362)

pulsating variable star A star whose luminosity varies in a predictable, periodic way. (p. 393)

P-waves Pressure waves from an earthquake that travel rapidly through liquids and solids.

pyrolific-release experiment Experiment to look for life on Mars. Radioactively tagged carbon dioxide was added to Martian soil specimens. Scientists looked for indications that the radioactive material had been absorbed.

Q

quantization The fact that light and matter on small scales behave in a discontinuous manner and manifest themselves in the form of tiny "packets" of energy, called quanta.

quantum fluctuation Temporary random change in the amount of energy at a point in space.

quantum gravity Theory combining general relativity with quantum mechanics.

quantum mechanics The laws of physics as they apply on atomic scales.

quark A fundamental matter particle that interacts via the strong force; basic constituent of protons and neutrons.

quark epoch Period when all heavy elementary particles (composed of quarks) were in thermal equilibrium with the cosmic radiation field.

quarter Moon Lunar phase in which the Moon appears as a half disk. (p. 14)

quasar Starlike radio source with an observed redshift that indicates an extremely large distance from Earth. The brightest nucleus of a distant active galaxy. (p. 439)

quasar feedback The idea that some of the energy released by a quasar in an active galactic nucleus heats and ejects the gas in the surrounding galaxy, shutting off the quasar fuel supply and suppressing star formation in the galaxy, connecting the growth of the central black hole to the properties of the host galaxy. (p. 461)

quasi-stellar object (QSO) *See* quasar.

quiescent prominence Prominence that persists for days or weeks, hovering high above the solar photosphere.

quiet Sun The underlying predictable elements of the Sun's behavior, such as its average photospheric temperature, which do not change in time.

R

radar Acronym for RAdio Detection And Ranging. Radio waves are bounced off an object, and the time taken for the echo to return indicates its distance. (p. 36)

radial motion Motion along a particular line of sight, which induces apparent changes in the wavelength (or frequency) of radiation received.

radial velocity Component of a star's velocity along the line of sight.

radian Angular measure equivalent to $180/\pi = 57.3$ degrees.

radiant Constellation from which a meteor shower appears to come.

radiation A way in which energy is transferred from place to place in the form of a wave. Light is a form of electromagnetic radiation.

radiation darkening The effect of chemical reactions that result when high-energy particles strike the icy surfaces of objects in the outer solar system. The reactions lead to a buildup of a dark layer of material.

radiation-dominated universe Early epoch in the universe, when the equivalent density of radiation in the cosmos exceeded the density of matter. (p. 489)

radiation era The first few thousand years after the Big Bang when the universe was small, dense, and dominated by radiation.

radiation zone Region of the Sun's interior where extremely high temperatures guarantee that the gas is completely ionized. Photons only occasionally interact with electrons and travel through this region with relative ease. (p. 254)

radio Region of the electromagnetic spectrum corresponding to radiation of the longest wavelengths. (p. 46)

radioactivity The release of energy by rare, heavy elements when their nuclei decay into lighter nuclei. (p. 151)

radio galaxy Type of active galaxy that emits most of its energy in the form of long-wavelength radiation. (p. 434)

radiograph Image made from observations at radio wavelengths.

radio lobe Roundish extended region of radio-emitting gas, lying well beyond the center of a radio galaxy. (p. 434)

radio telescope Large instrument designed to detect radiation from space at radio wavelengths. (p. 84)

radio wave Electromagnetic radiation with wavelength in the radio part of the spectrum (p. 46)

radius–luminosity–temperature relationship A mathematical proportionality, arising from Stefan's law, that allows astronomers to indirectly determine the radius of a star once its luminosity and temperature are known. (p. 289)

rapid mass transfer Mass transfer in a binary system that proceeds at a rapid and unstable rate, transferring most of the mass of one star onto the other.

ray The path taken by a beam of radiation.

Rayleigh scattering Scattering of light by particles in the atmosphere.

recession velocity Rate at which two objects are separating from one another.

recurrent nova Star that "goes nova" several times over the course of a few decades.

reddening Dimming of starlight by interstellar matter, which tends to scatter higher-frequency (blue) components of the radiation more efficiently than the lower-frequency (red) components. (p. 305)

red dwarf Small, cool, faint star at the lower-right end of the main sequence on the Hertzsprung–Russell diagram. (p. 290)

red giant A giant star whose surface temperature is relatively low so that it glows red. (p. 289)

red giant branch The section of the evolutionary track of a star corresponding to intense hydrogen shell burning, which drives a steady expansion and cooling of the outer envelope of the star. As the star gets larger in radius and its surface temperature cools, it becomes a red giant. (p. 334)

red giant region The upper-right corner of the Hertzsprung–Russell diagram, where red giant stars are found. (p. 291)

redshift Motion-induced change in the wavelength of light emitted from a source moving away from us. The relative recessional motion causes the wave to have an observed wavelength longer (and hence redder) than it would if it were not moving.

redshift survey Three-dimensional survey of galaxies, using redshift to determine distance.

red supergiant An extremely luminous red star. Often found on the asymptotic giant branch of the Hertzsprung–Russell diagram. (pp. 289, 342)

reflecting telescope A telescope that uses a mirror to gather and focus light from a distant object. (p. 72)

reflection nebula Bluish nebula caused by starlight scattering from dust particles in an interstellar cloud located just off the line of sight between Earth and a bright star.

refracting telescope A telescope that uses a lens to gather and focus light from a distant object. (p. 72)

refraction The tendency of a wave to bend as it passes from one transparent medium to another. (p. 72)

regolith Surface dust on the moon, several tens of meters thick in places, caused by billions of years of meteoritic bombardment.

relativistic Speeds comparable to the speed of light.

relativistic fireball Leading explanation of a gamma-ray burst in which an expanding region of superhot gas radiates in the gamma-ray part of the spectrum.

residual cap Portion of Martian polar ice caps that remains permanently frozen, undergoing no seasonal variations.

resonance Circumstance in which two characteristic times are related in some simple way, e.g., an asteroid with an orbital period exactly half that of Jupiter.

retina (eye) The back part of the eye onto which light is focused by the lens.

retrograde motion Backward, westward loop traced out by a planet with respect to the fixed stars. (p. 28)

revolution Orbital motion of one body about another, such as Earth about the Sun. (p. 9)

revolving *See* revolution.

Riemannian geometry Geometry of positively curved space (such as the surface of a sphere).

right ascension Celestial coordinate used to measure longitude on the celestial sphere. The zero point is the position of the Sun at the vernal equinox. (p. 8)

rille A ditch on the surface of the Moon where molten lava flowed in the past.

ring *See* planetary ring system.

ringlet Narrow region in Saturn's planetary ring system where the density of ring particles is high. *Voyager* discovered that the rings visible from Earth are actually composed of tens of thousands of ringlets. (p. 240)

Roche limit Often called the tidal stability limit, the Roche limit gives the distance from a planet at which the tidal force (due to the planet) between adjacent objects exceeds their mutual attraction. Objects within this limit are unlikely to accumulate into larger objects. The rings of Saturn occupy the region within Saturn's Roche limit. (p. 239)

Roche lobe An imaginary surface around a star. Each star in a binary system can be pictured as being surrounded by a teardrop-shaped zone of gravitational influence, the Roche lobe. Any material within the Roche lobe of a star can be considered to be part of that star. During evolution, one member of the binary system can expand so that it overflows its own Roche lobe and begins to transfer matter onto the other star.

rock Material made predominantly from compounds of silicon and oxygen.

rock cycle Process by which surface rock on Earth is continuously redistributed and transformed from one type into another.

rotation Spinning motion of a body about an axis. (p. 7)

rotation curve Plot of the orbital speed of disk material in a galaxy against its distance from the galactic center. Analysis of rotation curves of spiral galaxies indicates the existence of dark matter. (p. 406)

R-process "Rapid" process in which many neutrons are captured by a nucleus during a supernova explosion.

RR Lyrae variable Variable star whose luminosity changes in a characteristic way. All RR Lyrae stars have more or less the same average luminosity. (p. 394)

runaway greenhouse effect A process in which the heating of a planet leads to an increase in its atmosphere's ability to retain heat and thus to further heating, causing extreme changes in the temperature of the surface and the composition of the atmosphere. (p. 194)

runoff channel Riverlike surface feature on Mars, evidence that liquid water once existed there in great quantities. They are found in the southern highlands and are thought to have been formed by water that flowed nearly 4 billion years ago. (p. 184)

S

S0 galaxy Galaxy that shows evidence of a thin disk and a bulge, but that has no spiral arms and contains little or no gas. (p. 423)

Sagittarius A/Sgr A Strong radio source corresponding to the supermassive black hole at the center of the Milky Way.

Saros cycle Time interval between successive occurrences of the "same" solar eclipse, equal to 18 years, 11.3 days.

satellite A small body orbiting another larger body.

SB0 galaxy An S0-type galaxy whose disk shows evidence of a bar. (p. 423)

scarp Surface feature on Mercury believed to be the result of cooling and shrinking of the crust forming a wrinkle on the face of the planet. (p. 175)

Schmidt telescope Type of telescope having a very wide field of view, allowing large areas of the sky to be observed at once.

Schwarzschild radius The distance from the center of an object such that, if all the mass were compressed within that region, the escape speed would equal the speed of light. Once a stellar remnant collapses within this radius, light cannot escape and the object is no longer visible. (p. 374)

science A step-by-step process for investigating the physical world based on natural laws and observed phenomena. (p. 20)

scientific method The set of rules used to guide science, based on the idea that scientific "laws" be continually tested and modified or replaced if found inadequate. (p. 20)

scientific notation Expressing large and small numbers using power-of-10 notation.

seasonal cap Portion of Martian polar ice caps that is subject to seasonal variations, growing and shrinking once each Martian year.

seasons Changes in average temperature and length of day that result from the tilt of Earth's (or any planet's) axis with respect to the plane of its orbit. (p. 11)

secondary atmosphere The chemicals that composed Earth's atmosphere after the planet's formation, once volcanic activity outgassed chemicals from the interior. (p. 193)

sedimentary Rocks formed from the buildup of sediment.

seeing A term used to describe the ease with which good telescopic observations can be made from Earth's surface, given the blurring effects of atmospheric turbulence. (p. 83)

seeing disk Roughly circular region on a detector over which a star's pointlike images is spread, due to atmospheric turbulence. (p. 83)

seismic wave A wave that travels outward from the site of an earthquake through Earth. (p. 149)

seismology The study of earthquakes and the waves they produce in Earth's interior.

seismometer Equipment designed to detect and measure the strength of earthquakes (or quakes on any other planet).

selection effect Observational bias in which a measured property of a collection of objects is due to the way in which the measurement was made, rather than being intrinsic to the objects themselves. (p. 131)

self-propagating star formation Mode of star formation in which shock waves produced by the formation and evolution of one generation of stars triggers the formation of the next. (p. 403)

semidetached binary Binary system where one star lies within its Roche lobe but the other fills its Roche lobe and is transferring matter onto the first star.

semimajor axis One-half of the major axis of an ellipse. The semimajor axis is the way in which the size of an ellipse is usually quantified. (p. 34)

SETI Acronym for Search for Extraterrestrial Intelligence.

Seyfert galaxy Type of active galaxy whose emission comes from a very small region within the nucleus of an otherwise normal-looking spiral system. (p. 433)

shepherd satellite Satellite whose gravitational effect on a ring helps preserve the ring's shape. Examples are two satellites of Saturn, Prometheus and Pandora, whose orbits lie on either side of the F ring. (p. 241)

shield volcano A volcano produced by repeated nonexplosive eruptions of lava, creating a gradually sloping, shield-shaped low dome. Often contains a caldera at its summit. (p. 177)

shock wave Wave of matter, which may be generated by a newborn star or supernova, that pushes material outward into the surrounding molecular cloud. The material tends to pile up, forming a rapidly moving shell of dense gas.

short-period comet Comet with orbital period less than 200 years.

SI Système International d'unitès, the international system of metric units used to define mass, length, time, etc.

sidereal day The time needed between successive risings of a given star. (p. 9)

sidereal month Time required for the Moon to complete one trip around the celestial sphere. (p. 14)

sidereal year The time required for the constellations to complete one cycle around the sky and return to their starting points, as seen from a given point on Earth. Earth's orbital period around the Sun is 1 sidereal year. (p. 12)

single-line spectroscopic binary Binary system in which one star is too faint for its spectrum to be distinguished, so only the spectrum of the brighter star can be seen to shift back and forth as the stars orbit one another.

singularity A point in the universe where the density of matter and the gravitational field are infinite, such as at the center of a black hole. (p. 382)

sister/coformation theory (Moon) Theory suggesting that the Moon formed as a separate object close to Earth.

soft landing Use of rockets, parachutes, or packaging to break the fall of a space probe as it lands on a planet.

solar activity Unpredictable, often violent events on or near the solar surface, associated with magnetic phenomena on the Sun. (p. 262)

solar constant The amount of solar energy reaching Earth per unit area per unit time, approximately 1400 W/m^2. (p. 255)

solar core The region at the center of the Sun, with a radius of nearly 200,000 km, where powerful nuclear reactions generate the Sun's energy output.

solar cycle The 22-year period that is needed for both the average number of spots and the Sun's magnetic polarity to repeat themselves. The Sun's polarity reverses on each new 11-year sunspot cycle. (p. 265)

solar day The period of time between the instant when the Sun is directly overhead (i.e., noon) to the next time it is directly overhead. (p. 9)

solar eclipse Celestial event during which the new Moon passes directly between Earth and the Sun, temporarily blocking the Sun's light. (p. 16)

solar interior The region of the Sun between the solar core and the photosphere.

solar maximum Point of the sunspot cycle during which many spots are seen. They are generally confined to regions in each hemisphere, between about 15 and 20 degrees latitude.

solar minimum Point of the sunspot cycle during which only a few spots are seen. They are generally confined to narrow regions in each hemisphere at about 25–30 degrees latitude.

solar nebula The swirling gas surrounding the early Sun during the epoch of solar system formation, also referred to as the primitive solar system. (p. 121)

solar neutrino problem The discrepancy between the theoretically predicted flux of neutrinos streaming from the Sun as a result of fusion reactions in the core and the flux that is actually observed. The observed number of neutrinos is only about half the predicted number. (p. 274)

solar system The Sun and all the bodies that orbit it—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, their moons, the asteroids, the Kuiper belt, and the comets. (p. 104)

solar wind An outward flow of fast-moving charged particles from the Sun. (pp. 113, 254)

solstice *See* summer solstice; winter solstice.

south celestial pole Point on the celestial sphere directly above Earth's South Pole. (p. 8)

spacetime Single entity combining space and time in special and general relativity.

spatial resolution The dimension of the smallest detail that can be seen in an image.

special relativity Theory proposed by Einstein to deal with the preferred status of the speed of light.

speckle interferometry Technique whereby many short-exposure images of a star are combined to make a high-resolution map of the star's surface.

spectral class Classification scheme, based on the strength of stellar spectral lines, which is an indication of the temperature of a star. (p. 287)

spectral window Wavelength range in which Earth's atmosphere is transparent.

spectrograph Instrument used to produce detailed spectra of stars. Usually, a spectrograph records a spectrum on a CCD detector, for computer analysis.

spectrometer Instrument used to produce detailed spectra of stars. Usually, a spectrograph records a spectrum on a photographic plate, or more recently, in electronic form on a computer.

spectroscope Instrument used to view a light source so that it is split into its component colors. (p. 56)

spectroscopic binary A binary-star system that appears as a single star from Earth, but whose spectral lines show back-and-forth Doppler shifts as two stars orbit one another. (p. 295)

spectroscopic parallax Method of determining the distance to a star by measuring its temperature and then determining its absolute brightness by comparing with a standard Hertzsprung–Russell diagram. The absolute and apparent brightness of the star give the star's distance from Earth. (p. 293)

spectroscopy The study of the way in which atoms absorb and emit electromagnetic radiation. Spectroscopy allows astronomers to determine the chemical composition of stars. (p. 58)

spectrum The separation of light into its component colors.

speed Distance moved per unit time, independent of direction. *See also* velocity.

speed of light The fastest possible speed, according to the currently known laws of physics. Electromagnetic radiation exists in the form of waves or photons moving at the speed of light. (p. 49)

spicule Small solar storm that expels jets of hot matter into the Sun's lower atmosphere.

spin–orbit resonance State that a body is said to be in if its rotation period and its orbital period are related in some simple way.

spiral arm Distribution of material in a galaxy forming a pinwheel-shaped design, beginning near the galactic center. (p. 401)

spiral density wave A wave of matter formed in the plane of planetary rings, similar to ripples on the surface of a pond, that wraps around the rings, forming spiral patterns similar to grooves in a record disk. Spiral density waves can lead to the appearance of ringlets. (p. 402)

A proposed explanation for the existence of galactic spiral arms, in which coiled waves of gas compression move through the galactic disk, triggering star formation.

spiral galaxy Galaxy composed of a flattened, star-forming disk component that may have spiral arms and a large central galactic bulge. (p. 421)

spiral nebula Historical name for spiral galaxies, describing their appearance.

spring tide The largest tides, occurring when the Sun, Moon, and Earth are aligned at new and full Moon.

S-process "Slow" process in which neutrons are captured by a nucleus; the rate is typically one neutron capture per year.

standard candle Any object with an easily recognizable appearance and known luminosity, which can be used in estimating distances.

Supernovae, which all have the same peak luminosity (depending on type), are good examples of standard candles and are used to determine distances to other galaxies. (p. 426)

standard solar model A self-consistent picture of the Sun, developed by incorporating the important physical processes that are believed to be important in determining the Sun's internal structure into a computer program. The results of the program are then compared with observations of the Sun, and modifications are made to the model. The standard solar model, which enjoys widespread acceptance, is the result of this process. (p. 255)

standard time System of dividing Earth's surface into 24 time zones, with all clocks in each zone keeping the same time.

star A glowing ball of gas held together by its own gravity and powered by nuclear fusion in its core. (pp. 6, 254)

starburst galaxy Galaxy in which a violent event, such as near collision, has caused an intense episode of star formation in the recent past. (p. 451)

star cluster A grouping of anywhere from a dozen to a million stars that formed at the same time from the same cloud of interstellar gas. Stars in clusters are useful to aid our understanding of stellar evolution because, within a given cluster, stars are all roughly the same age and chemical composition and lie at roughly the same distance from Earth. (p. 323)

Stefan's law Relation that gives the total energy emitted per square centimeter of its surface per second by an object of a given temperature. Stefan's law shows that the energy emitted increases rapidly with an increase in temperature, proportional to the temperature raised to the fourth power. (p. 54)

stellar epoch Most recent period, when stars, planets, and life have appeared in the universe.

stellar nucleosynthesis The formation of heavy elements by the fusion of lighter nuclei in the hearts of stars. Except for hydrogen and helium, all other elements in our universe resulted from stellar nucleosynthesis.

stellar occultation The dimming of starlight produced when a solar system object such as a planet, moon, or ring passes directly in front of a star. (p. 241)

stratosphere The portion of Earth's atmosphere lying above the troposphere, extending up to an altitude of 40–50 km. (p. 144)

string theory Theory that interprets all particles and forces in terms of particular modes of vibration of submicroscopic strings.

strong nuclear force Short-range force responsible for binding atomic nuclei together. The strongest of the four fundamental forces of nature. (p. 271)

S-type asteroid Asteroid made up mainly of silicate or rocky material.

subatomic particle Particle smaller than the size of an atomic nucleus.

subduction zone Place where two plates meet and one slides under the other.

subgiant branch The section of the evolutionary track of a star that corresponds to changes that occur just after hydrogen is depleted in the core, and core hydrogen burning ceases. Shell hydrogen burning heats the outer layers of the star, which causes a general expansion of the stellar envelope. (p. 334)

sublimation Process by which element changes from the solid to the gaseous state, without becoming liquid.

summer solstice Point on the ecliptic where the Sun is at its northernmost point above the celestial equator, occurring on or near June 21. (p. 10)

sunspot An Earth-sized dark blemish found on the surface of the Sun. The dark color of the sunspot indicates that it is a region of lower temperature than its surroundings. (p. 262)

sunspot cycle The fairly regular pattern that the number and distribution of sunspots follows, in which the average number of spots reaches a maximum every 11 or so years, then falls off to almost zero. (p. 265)

supercluster Grouping of several clusters of galaxies into a larger, but not necessarily gravitationally bound unit. (p. 463)

super-Earth An extrasolar planet with a mass between 2 and 10 times that of Earth. (p. 130)

superforce An attempt to combine the strong and electroweak forces into one single force.

supergiant A star with a radius between 100 and 1000 times that of the Sun. (p. 289)

supergranulation Large-scale flow pattern on the surface of the Sun, consisting of cells measuring up to 30,000 km across, believed to be the imprint of large convective cells deep in the solar interior. (p. 259)

superior conjunction Orbital configuration in which an inferior planet (Mercury or Venus) lies farthest from Earth (on the opposite side of the Sun).

supermassive black hole Black hole having a mass a million to a billion times greater than the mass of the Sun; usually found in the central nucleus of a galaxy.

supernova Explosive death of a star, caused by the sudden onset of nuclear burning (Type I), or an enormously energetic shock wave (Type II). One of the most energetic events of the universe, a supernova may temporarily outshine the rest of the galaxy in which it resides. (p. 344)

supernova remnant The scattered glowing remains from a supernova that occurred in the past. The Crab Nebula is one of the best-studied supernova remnants. (p. 347)

supersymmetric relic Massive particles that should have been created in the Big Bang if supersymmetry is correct.

surface gravity The acceleration due to gravity at the surface of a star or planet. (p. 140)

S-waves Shear waves from an earthquake, which can travel only through solid material and move more slowly than p-waves.

synchronous orbit State of an object when its period of rotations is exactly equal to its average orbital period. The Moon is in a synchronous orbit and so presents the same face toward Earth at all times. (p. 142)

synchrotron radiation Type of nonthermal radiation produced by high-speed charged particles, such as electrons, as they are accelerated in a strong magnetic field. (p. 441)

synodic month Time required for the Moon to complete a full cycle of phases. (p. 14)

synodic period Time required for a body to return to the same apparent position relative to the Sun, taking Earth's own motion into account; the time between one closest approach to Earth and the next (for a planet).

T

T Tauri phase star Protostar in the late stages of formation, often exhibiting violent surface activity. T Tauri phase stars have been observed to brighten noticeably in a short period of time, consistent with the idea of rapid evolution during this final phase of stellar formation. (p. 319)

tail Component of a comet that consists of material streaming away from the main body, sometimes spanning hundreds of millions of kilometers. May be composed of dust or ionized gases. (p. 112)

tau A type of lepton (along with the electron and muon).

tectonic fracture Cracks on a planet's surface, in particular on the surface of Mars, caused by internal geological activity.

telescope Instrument used to capture as many photons as possible from a given region of the sky and concentrate them into a focused beam for analysis. (p. 72)

temperature A measure of the amount of heat in an object, and an indication of the speed of the particles that comprise it. (p. 53)

tenuous Thin, having low density.

terminator The line separating night from day on the surface of the Moon or a planet.

terrae *See* highlands.

terrestrial planet One of the four innermost planets of the solar system, resembling Earth in general physical and chemical properties. (p. 106)

theoretical model An attempt to construct a mathematical explanation of a physical process or phenomenon within the assumptions and confines of a given theory. In addition to providing an explanation of the observed facts, the model generally also makes new predictions that can be tested by further observation or experimentation. (p. 20)

theories of relativity Einstein's theories, on which much of modern physics rests. Two essential facts of the theory are that nothing can travel faster than the speed of light and that everything, including light, is affected by gravity.

theory A framework of ideas and assumptions used to explain some set of observations and make predictions about the real world. (p. 20)

thermal equilibrium Condition in which new particle–antiparticle pairs are created from photons at the same rate as pairs annihilate one another to produce new photons.

thick disk Region of a spiral galaxy where an intermediate population of stars resides, younger than the halo stars but older than stars in the disk.

threshold temperature Critical temperature above which pair production is possible and below which pair production cannot occur.

tidal bulge Elongation of Earth caused by the difference between the gravitational force on the side nearest the Moon and the force on the side farthest from the Moon. The long axis of the tidal bulge points toward the Moon. More generally, the deformation of any body produced by the tidal effect of a nearby gravitating object. (p. 141)

tidal force The variation in one body's gravitational force from place to place across another body—for example, the variation of the Moon's gravity across Earth. (p. 141)

tidal locking Circumstance in which tidal forces have caused a moon to rotate at exactly the same rate at which it revolves around its parent planet, so that the moon always keeps the same face turned toward the planet. (p. 142)

tidal stability limit The minimum distance within which a moon can approach a planet before being torn apart by the planet's tidal force.

tidally locked Condition in which tidal forces have caused a body (such as a moon) to rotate at exactly the same rate at which it orbits another body so that it always keeps the same face toward the other body. (p. 142)

tides Rising and falling motion of terrestrial bodies of water, exhibiting daily, monthly, and yearly cycles. Ocean tides on Earth are caused by the competing gravitational pull of the Moon and Sun on different parts of Earth. (p. 141)

time dilation A prediction of the theory of relativity, closely related to the gravitational reshift. To an outside observer, a clock lowered into a strong gravitational field will appear to run slow. (p. 381)

time zone Region on Earth in which all clocks keep the same time, regardless of the precise position of the Sun in the sky, for consistency in travel and communications.

total eclipse Celestial event during which one body is completely blocked from view by another. (p. 16)

transit Orbital configuration where a planet (i.e., Mercury or Venus) passes between Earth and the Sun.

transition zone The region of rapid temperature increases that separates the Sun's chromosphere from the corona. (p. 254)

transverse motion Motion perpendicular to a particular line of sight, which does not result in Doppler shift in radiation received.

transverse velocity Component of star's velocity perpendicular to the line of sight.

triangulation Method of determining distance based on the principles of geometry. A distant object is sighted from two well-separated locations. The distance between the two locations and the angle between the line joining them and the line to the distant object are all that are necessary to ascertain the object's distance. (p. 18)

triple-alpha process The creation of carbon-12 by the fusion of three helium-4 nuclei (alpha particles). Helium-burning stars occupy a region of the Hertzsprung–Russell diagram known as the horizontal branch.

triple star system Three stars that orbit one another, bound together by gravity.

Trojan asteroid One of two groups of asteroids that orbit at the same distance from the Sun as Jupiter, 60 degrees ahead of and behind the planet. (p. 108)

tropical year The time interval between one vernal equinox and the next. (p. 12)

troposphere The portion of Earth's atmosphere from the surface to about 15 km. (p. 144)

trough Maximum departure of a wave below its undisturbed state.

true space motion True motion of a star, taking into account both its transverse and radial motion according to the Pythagorean theorem.

Tully-Fisher relation A relation used to determine the absolute luminosity of a spiral galaxy. The rotational velocity, measured from the broadening of spectral lines, is related to the total mass, and hence the total luminosity. (p. 427)

turnoff mass The mass of a star that is just now evolving off the main sequence in a star cluster.

21-centimeter line Spectral line in the radio region of the electromagnetic spectrum associated with a change of spin of the electron in a hydrogen atom. (p. 313)

21-centimeter radiation Radio radiation emitted when an electron in the ground state of a hydrogen atom flips its spin to become parallel to the spin of the proton in the nucleus.

twin quasar Quasar that is seen twice at different locations in the sky due to gravitational lensing.

Type I supernova One possible explosive death of a star. A white dwarf in a binary star system can accrete enough mass that it cannot support its own weight. The star collapses and temperatures become high enough for carbon fusion to occur. Fusion begins throughout the white dwarf almost simultaneously, and an explosion results. (p. 345)

Type II supernova One possible explosive death of a star, in which the highly evolved stellar core rapidly implodes and then explodes, destroying the surrounding star. (p. 345)

U

ultraviolet Region of the electromagnetic spectrum, just beyond the visible range, corresponding to wavelengths slightly shorter than blue light. (p. 46)

ultraviolet telescope A telescope that is designed to collect radiation in the ultraviolet part of the spectrum. Earth's atmosphere is partially opaque to these wavelengths, so ultraviolet telescopes are put on rockets, balloons, and satellites to get high above most or all of the atmosphere. (p. 92)

umbra Central region of the shadow cast by an eclipsing body.

The central region of a sunspot, which is its darkest and coolest part. (p. 16)

unbound An orbit that does not stay in a specific region of space, but where an object escapes the gravitational field of another. Typical unbound orbits are hyperbolic in shape.

unbound trajectory Path of an object with launch speed high enough that it can escape the gravitational pull of a planet.

uncompressed density The density a body would have in the absence of any compression due to its own gravity.

universal time Mean solar time at the Greenwich meridian.

universe The totality of all space, time, matter, and energy. (p. 6)

unstable nucleus Nucleus that cannot exist indefinitely, but rather must eventually decay into other particles or nuclei.

upwelling Upward motion of material having temperature higher than the surrounding medium.

V

vacuum energy Property of empty space when it is excited above its normal zero-energy state. Astronomers think that the temporary appearance of vacuum energy was responsible for one or more periods of inflation during the early universe. (p. 492)

Van Allen belts At least two doughnut-shaped regions of magnetically trapped, charged particles high above Earth's atmosphere. (p. 159)

variable star A star whose luminosity changes with time. (p. 394)

velocity Displacement (distance plus direction) per unit time. *See also* speed.

vernal equinox Date on which the Sun crosses the celestial equator moving northward, occurring on or near March 21. (p. 12)

visible light The small range of the electromagnetic spectrum that human eyes perceive as light. The visible spectrum ranges from about 400 to 700 nm, corresponding to blue through red light. (p. 46)

visible spectrum The small range of the electromagnetic spectrum that human eyes perceive as light. The visible spectrum ranges from about 4000 to 7000 angstroms, corresponding to blue through red light.

visual binary A binary star system in which both members are resolvable from Earth. (p. 295)

void Large, relatively empty region of the universe around which superclusters and "walls" of galaxies are organized. (p. 464)

volcano Upwelling of hot lava from below Earth's crust to the planet's surface. (p. 150)

W

wane (referring to the Moon or a planet) To shrink. The Moon appears to wane, or shrink in size, for 2 weeks after full Moon.

warm longitudes (Mercury) Two opposite points on Mercury's equator where the Sun is directly overhead at aphelion. Cooler than the hot longitudes by 150 degrees.

water hole The radio interval between 18 cm and 21 cm, the respective wavelengths at which hydroxyl (OH) and hydrogen (H) radiate, in which intelligent civilizations might conceivably send their communication signals. (p. 518)

water volcano Volcano that ejects water (molten ice) rather than lava (molten rock) under cold conditions.

watt/kilowatt Unit of power: 1 watt (W) is the emission of 1 joule (J) per second; 1 kilowatt (kW) is 1000 watts.

wave A pattern that repeats itself cyclically in both time and space. Waves are characterized by the speed at which they move, their frequency, and their wavelength. (p. 46)

wavelength The distance from one wave crest to the next, at a given instant in time. (p. 47)

wave period The amount of time required for a wave to repeat itself at a specific point in space. (p. 47)

wave theory of radiation Description of light as a continuous wave phenomenon, rather than as a stream of individual particles.

wax (referring to the Moon or a planet) To grow. The Moon appears to wax, or grow in size, for 2 weeks after new Moon.

weakly interacting massive particle (WIMP) Class of subatomic particles that might have been produced early in the history of the universe; dark-matter candidates.

weak nuclear force Short-range force, weaker than both electromagnetism and the strong force, but much stronger than gravity; responsible for certain nuclear reactions and radioactive decays. (p. 271)

weight The gravitational force exerted on you by Earth (or the planet on which you happen to be standing).

weird terrain A region on the surface of Mercury with oddly rippled features. This feature is thought to be the result of a strong impact that occurred on the other side of the planet and sent seismic waves traveling around the planet, converging in the weird region.

white dwarf A dwarf star with sufficiently high surface temperature that it glows white. (p. 289)

white dwarf region The bottom-left corner of the Hertzsprung–Russell diagram, where white dwarf stars are found. (p. 291)

white oval Light-colored region near the Great Red Spot in Jupiter's atmosphere. Like the red spot, such regions are apparently rotating storm systems. (p. 211)

Wien's law Relation between the wavelength at which a blackbody curve peaks and the temperature of the emitter. The peak wavelength is inversely proportional to the temperature, so the hotter the object, the bluer its radiation. (p. 54)

winter solstice Point on the ecliptic where the Sun is at its southernmost point below the celestial equator, occurring on or near December 21. (p. 11)

wispy terrain Prominent light-colored streaks on Rhea, one of Saturn's moons.

X

X-ray Region of the electromagnetic spectrum corresponding to radiation of high frequency and short wavelength, far beyond the visible spectrum. (p. 46)

X-ray burster X-ray source that radiates thousands of times more energy than our Sun in short bursts lasting only a few seconds. A neutron star in a binary system accretes matter onto its surface until temperatures reach the level needed for hydrogen fusion to occur. The result is a sudden period of rapid nuclear burning and release of energy. (p. 366)

X-ray nova Nova explosion detected at X-ray wavelengths.

Z

Zeeman effect Broadening or splitting of spectral lines due to the presence of a magnetic field.

zero-age main sequence The region on the Hertzsprung–Russell diagram, as predicted by theoretical models, where stars are located at the onset of nuclear burning in their cores. (p. 322)

zodiac The 12 constellations on the celestial sphere through which the Sun appears to pass during the course of a year. (p. 10)

zonal flow Alternating regions of westward and eastward flow, roughly symmetrical about the equator of Jupiter, associated with the belts and zones in the planet's atmosphere. (p. 209)

zone Bright, high-pressure region in the atmosphere of a jovian planet, where gas flows upward. (p. 209)

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Answers to Check Questions

Concept Checks and Process of Science Checks

Chapter 0

1. (p. 8) (1) Because the celestial sphere provides a natural means of specifying the locations of stars on the sky. Celestial coordinates are directly related to Earth's orientation in space but are independent of Earth's rotation. (2) Distance information is lost. 2. (p. 13) Because of the tilt of Earth's rotation axis, the Sun is highest in the northern sky during northern summer, and the days are longest. 3. (p. 17) (1) The angular size of the Moon would remain the same, but that of the Sun would be halved, making it easier for the Moon to eclipse the Sun. We would expect to see total or partial eclipses, but no annular ones. (2) If the distance were halved, the angular size of the Sun would double, and total eclipses would never be seen—only partial or annular ones. 4. (p. 20) Because astronomical objects are too distant for direct ("measuring tape") measurements, we must rely on indirect means and mathematical reasoning. 5. (p. 23) A theory can never become proven "fact," because it can always be invalidated, or forced to change by a single contradictory observation. However, once a theory's predictions have been repeatedly verified by experiments over many years, it is often widely regarded as "true."

Chapter 1

1. (p. 32) In the geocentric view, retrograde motion is a real backward motion of a planet as it moves on its epicycle. In the heliocentric view, the backward motion is only apparent, caused by Earth "overtaking" the planet in its orbit. 2. (p. 31) Mainly simplicity and elegance. Both theories made testable predictions, and until Newton developed his laws, neither could explain *why* the planets move as they do. However, Copernicus's model was much simpler than the Ptolemaic version, which became more and more convoluted as observations improved. 3. (p. 33) The discovery of the phases of Venus could not be reconciled with the geocentric model. Observations of Jupiter's moons proved that some objects in the universe did not orbit Earth. 4. (p. 35) Galileo was an experimentalist; Kepler was a theorist. Galileo found observational evidence supporting the Copernican theory; Kepler found an empirical description of the motions of the planets within the Copernican picture that greatly simplified the theoretical view of the solar system. 5. (p. 36) Because those planets were unknown to Kepler. The fact that the laws apply to the outer planets then constitutes a prediction subsequently verified by observation. 6. (p. 36) Because Kepler determined the overall geometry of the solar system by triangulation using Earth's orbit as a baseline, all distances were known only relative to the scale of Earth's orbit—the astronomical unit (AU). 7. (p. 39) In the absence of any force, a planet would move in a straight line with constant velocity (Newton's first law) and therefore tends to move along the tangent to its orbital path. The Sun's gravity causes the planet to accelerate toward the Sun (Newton's second law), bending its trajectory into the orbit we observe. 8. (p. 41) Kepler's laws were accurate descriptions of planetary motion based on observations, but they contained no insight into *why* the planets orbited the Sun or why the orbits are as they are. Newtonian mechanics explained the orbits in terms of universal laws, and in addition made detailed predictions about the motion of other bodies in the cosmos—moons, comets, other stars—that were hitherto impossible to make.

Chapter 2

1. (p. 47) A wave is a way in which energy or information is transferred from place to place via a repetitive, regularly varying disturbance of some sort. A wave is characterized by its wavelength, frequency, velocity, and amplitude: the product of the first two always equals the third. 2. (p. 50) Light is an electromagnetic wave produced by accelerating charged particles. All waves on the list are characterized by their wave periods, frequencies, and wavelengths, and all carry energy and information from one location to another. Unlike waves in water or air, however, light waves require no physical medium through which to propagate. 3. (p. 53) All are electromagnetic radiation and travel at the speed of light. In physical terms, they differ only in frequency (or wavelength), although their effects on our bodies (or our detectors) differ greatly. 4. (p. 55) As the switch is turned and the temperature of the filament rises, the bulb's brightness increases rapidly, by Stefan's law, and it color shifts, by Wien's law, from invisible infrared to red to yellow to white. 5. (p. 57) They are characteristic frequencies (wavelengths) at which matter absorbs or emits photons of electromagnetic radiation. They are unique to each atom or molecule and thus provide a means of identifying the gas producing them. 6. (p. 62) Electron orbits can occur only at certain specific energies, and there is a ground state that has the lowest possible energy. Planetary orbits can have any energy. Planets can stay in any orbit indefinitely; in an atom the electron must eventually fall to the ground state, emitting electromagnetic radiation in the process. Planets may reasonably be thought of as having specific trajectories around the Sun—there is no ambiguity as to "where" a planet is. Electrons in an atom are smeared out into an electron cloud, and we can only talk of the electron's location in probabilistic terms. 7. (p. 63) The wave theory could not explain why atoms emit and absorb radiation at specific, unique wavelengths, rather than as a continuous beam. The key new insight of quantum theory was that, on microscopic scales, the properties of both matter and radiation are *quantized*. Specifically, the energy of an electron in an atom can only take on certain definite values, unique to the type of atom, and radiation exists in the form of *photons* of specific energies. When an electron changes energy within an atom, it does so by emitting or absorbing a photon of a definite energy, and hence *color*, directly connecting observations of atomic spectra to the particular atoms producing them. 8. (p. 64) Spectral lines correspond to transitions between specific orbitals within an atom. The structure of an atom determines the energies of these orbitals, and hence the possible transitions, and thus the energies (colors) of the photons involved. 9. (p. 65) Measuring masses in astronomy usually entails measuring the orbital speed of one object—a companion star or a planet, perhaps—around another. In most cases, the Doppler effect is an astronomer's only way of making such measurements. 10. (p. 66) Because, with few exceptions, spectral analysis is the only way we have of determining the physical conditions—composition, temperature, density, velocity, etc.—in a distant object. Without spectral analysis, astronomers would know next to nothing about the properties of stars and galaxies.

Chapter 3

1. (p. 80) Because large reflecting telescopes are easier to design, build, and maintain than refracting instruments. 2. (p. 83) The need to gather as much light as possible, and the need to achieve the highest possible angular resolution. 3. (p. 84) The atmosphere absorbs some radiation arriving from space, and turbulent motion blurs the incoming rays. To reduce or overcome the effects of atmospheric absorption, instruments are placed on high mountains or in space. To compensate for atmospheric turbulence, adaptive optics techniques probe the air above the observing site and adjust the mirror surface accordingly to try to recover the undistorted image. 4. (p. 87) Radio astronomy opens up a new window on the universe, allowing astronomers to study known objects in new ways and to discover new objects that would otherwise be completely unobservable. The faintness of the sources is addressed by combining the largest available telescopes with sensitive detectors. Resolution can be greatly improved by the use of interferometry, which combines the signals from two or more separate telescopes to create the effect of a single instrument of much larger diameter. 5. (p. 93) The text presents multiwavelength observations of stars, star-forming regions, and galaxies. We must study astronomical objects at many wavelengths because most emit radiation across the entire spectrum, and much of what we know is learned from studies of invisible radiation. 6. (p. 95) Benefits: They are above the atmosphere, so they are unaffected by seeing or absorption; they can also make round-the-clock observations of the entire sky. Drawbacks: Cost/smaller size, inaccessibility, vulnerability to damage by radiation and cosmic rays.

Chapter 4

1. (p. 107) Because the two classes of planets differ in almost every physical property—orbit, mass, radius, composition, existence of rings, number of moons. 2. (p. 111) Similarities: All orbit in the inner solar system, roughly in the ecliptic plane, and are solid bodies of generally "terrestrial" composition. Differences: Asteroids are much smaller than the terrestrial planets, are generally less evolved than the planets, and move on much less regular orbits. 3. (p. 115) Most comets never come close enough to the Sun for us to see them. 4. (p. 118) Because it is thought to be much less evolved than material now found in planets, and hence it is a better indicator of conditions in the early solar system. 5. (p. 120) Because it must explain certain general features of solar system architecture, while accommodating the fact that there are exceptions to many of them. 6. (p. 127) Yes. If a star formed with a disk of matter around it, then even if it doesn't have planets like Earth, the basic processes of condensation and accretion would probably have occurred there, too. 7. (p. 134) Because the search techniques are most sensitive to

massive planets orbiting close to their parent stars, which are exactly what have been observed.

Chapter 5

1. (p. 143) A tidal force is the *variation* in one body's gravitational force from place to place across another. Tidal forces tend to deform a body rather than causing an overall acceleration, and they decrease rapidly with distance. 2. (p. 147) It raises Earth's average surface temperature above the freezing point of water, which was critical for the development of life on our planet. Should the greenhouse effect continue to strengthen, however, it may conceivably cause catastrophic climate changes on Earth. 3. (p. 150) Earthquakes and seismic waves are observed on Earth's surface. These data are combined with models of how waves move through Earth's interior to construct a model of our planet's composition and physical state. We measure Earth's mass, radius, and surface composition directly. However, the composition and temperature of our planet's interior are inferred from models. 4. (p. 152) We would have far less detailed direct (from volcanoes) or indirect (from seismic studies following earthquakes) information on our planet's interior. 5. (p. 155) Convection currents in the upper mantle cause portions of Earth's crust—plates—to slide around on the surface. As the plates move and interact, they are responsible for volcanism, earthquakes, the formation of mountain ranges and ocean trenches, and the creation and destruction of oceans and continents. 6. (p. 157) The maria are younger, denser, and are much less heavily cratered than the highlands. 7. (p. 161) It tells us that the planet has a conducting, liquid core in which the magnetic field is continuously generated. 8. (p. 163) The Moon's small size, which is the main reason that the Moon (1) has lost its initial heat, making it geologically dead today, and (2) has insufficient gravity to retain an atmosphere.

Chapter 6

1. (p. 172) The Sun's tidal force has caused Mercury's rotation period to become exactly 2/3 of the orbital period and the rotation axis to be oriented exactly perpendicular to the planet's orbit plane. A synchronous orbit is not possible because of Mercury's eccentric orbit around the Sun. 2. (p. 174) Venus's atmosphere is much more massive, hotter, and denser than that of Earth, and is composed almost entirely of carbon dioxide. 3. (p. 175) Scarps are thought to have been formed when the planet's iron core cooled and contracted, causing the crust to crack. Faults on Earth are the result of tectonic activity. 4. (p. 179) No. They are mainly shield volcanoes formed by lava upwelling through "hot spots" in the crust and are not associated with plate tectonics (which is not observed on Venus). 5. (p. 183) Mercury: improved observations of the planet's surface led to a major revision of Mercury's rotation rate. Venus: observations of the atmosphere initially suggested a relatively mild climate; however, later radio studies of the surface revealed a hot, dry, inhospitable world. Mars: with improving observations, astronomers' ideas of the surface have evolved from an arid desert irrigated by canals built by intelligent beings, to a world now dry and geologically dead, but that once had liquid water and possibly even life on its surface. 6. (p. 190) Observations reveal evidence for dried-up rivers, outflow channels, and what may be ancient oceans, strongly suggesting that the surface was once warm enough and the atmosphere thick enough for large bodies of liquid water to exist on the planet's surface. Today most of the remaining water on Mars is frozen, underground or at the poles. 7. (p. 193) Venus probably has a large liquid metal core, but it rotates too slowly for a planetary dynamo to operate. Mars rotates rapidly but lacks a liquid metal core. 8. (p. 196) Both might have climates quite similar to that on Earth, as the greenhouse effect would probably not have run away on Venus, and the water in the Martian atmosphere might not have frozen and become permafrost.

Chapter 7

1. (p. 206) Uranus's orbit was observed to deviate from a perfect ellipse, leading astronomers to try to compute the mass and location of the body responsible for those discrepancies. That body was Neptune. 2. (p. 208) The magnetic field is generated by the motion of electrically conducting liquid in the deep interior and therefore presumably shares the rotation of that region of the planet. 3. (p. 214) Like weather systems on Earth, the belts and zones are regions of high and low pressure and are associated with convective motion. However, unlike storms on Earth, they wrap all the way around the planet because of Jupiter's rapid rotation. In addition, the clouds are arranged in three distinct layers, and the bright colors are the result of cloud chemistry unlike anything operating in Earth's atmosphere. Jupiter's spots are somewhat similar to hurricanes on Earth, but they are far larger and longer-lived. 4. (p. 215) Uranus's low temperature means that the planet's clouds lie deeper in the atmosphere, making them harder to distinguish from Earth. 5. (p. 219) We have no direct observations of the interiors of these worlds. Everything we know is derived from theoretical models of their interiors, coupled with observations of their masses, radii, and surface properties. 6. (p. 221) They all combine the two essential ingredients needed to operate a planetary dynamo: (1) rapid rotation, in all cases faster than Earth's rotation, and (2) conducting liquid interiors: metallic hydrogen in the cases of Jupiter and Saturn and "slushy" ice in the cases of Uranus and Neptune.

Chapter 8

1. (p. 230) Jupiter's gravitational field, via its tidal effect on the moons. 2. (p. 235) The haze layers high in the moon's dense atmosphere are opaque to visible light. The *Huygens* probe landed on the surface, and *Cassini*'s radar and infrared sensors can penetrate the haze. 3. (p. 237) They are all very heavily cratered—a result of the heavy bombardment that marked the clearing of the comets from the outer solar system. 4. (p. 243) The Roche limit is the radius inside of which a moon will be torn apart by tidal forces. Planetary rings are found inside the Roche limit, (most) moons outside. 5. (p. 245) They have similar masses, radii, composition, and perhaps also similar origins in the Kuiper belt. 6. (p. 247) Pluto, like Ceres, Eris, and a few other bodies in the outer solar system, orbits the Sun and is large enough for its gravity to have caused it to assume an approximately spherical shape, but it is not massive enough to have cleared its orbital path of other solar system objects. In current terminology, it is called a dwarf planet, or a plutoid.

Chapter 9

1. (p. 255) When we multiply the solar constant by the total area to obtain the solar luminosity, we are implicitly assuming that the same amount of energy reaches every square meter of the large sphere in Figure 9.3. 2. (p. 259) The energy may be carried in the form of (1) radiation, where energy travels in the form of light, and (2) convection, where energy is carried by physical motion of upwelling solar gas. 3. (p. 201) The coronal spectrum shows (1) emission lines of (2) highly ionized elements, implying high temperature. 4. (p. 270) There is a strong field, with a well-defined east-west organization, just below the surface. The field direction in the southern hemisphere is opposite that in the north. However, the details of the fields are very complex. 5. (p. 273) Because the Sun shines by nuclear fusion, which converts mass into energy as hydrogen turns into helium. 6. (p. 274) The solar neutrino problem was the fact that theory predicted that significantly more neutrinos should be detected coming from the Sun than were actually observed experimentally. Both the theory of solar nuclear fusion and the experimental apparatus on Earth were carefully checked and tested, and neither was found to be at fault. In the end, a new piece of the theory, explaining how neutrinos could change from one type to another en route from the core of the Sun to the detectors on Earth, accounted for the discrepancy and solved the problem.

Chapter 10

1. (p. 281) Because stars are so far away that their parallaxes relative to any baseline on Earth are too small to measure accurately. 2. (p. 285) Nothing—We need to know their distances before the luminosities (or absolute magnitudes) can be determined. 3. (p. 288) Even though the theory behind the classification was incorrect, it provided a very useful way to organize and categorize the large database of stellar observations, making it easy for astronomers to adapt and interpret the data when an improved understanding of atomic physics emerged some three decades later. 4. (p. 288) Because temperature controls which excited states the star's atoms and ions are in, and hence which atomic transitions are possible. 5. (p. 289) Yes, by using the radius–luminosity–temperature relationship, but only if we can find a method of determining the luminosity that doesn't depend on the inverse-square law (Sec. 10.2). 6. (p. 292) Because giants are intrinsically very luminous and can be seen to much greater distances than the more common main-sequence or white dwarfs. 7. (p. 293) All stars would be further away, but their measured spectral types and apparent brightnesses would presumably be unchanged, so their luminosities would be greater than previously thought. The main sequence would therefore move vertically upward in the H–R diagram. We would then use larger luminosities in the method of spectroscopic parallax, so distances inferred by that method would also increase. 8. (p. 294) We are assuming (1) that we can tell with some confidence whether or not an observed star lies on the main sequence, and (2) that the radius of a main-sequence star of a given spectral type is fairly well determined. Both assumptions are reasonable, although significant uncertainties exist, especially with assumption (2). 9. (p. 299) We don't. We assume that their masses are the same as similar stars found in binaries.

Chapter 11

1. (p. 307) Because the scale of interstellar space is so large that even very low densities can accumulate to a large amount of obscuring matter along the line of sight to a distant star. 2. (p. 311) Because the UV light is absorbed by hydrogen gas in the surrounding cloud, ionizing it to form the emission nebulae. The red light is H radiation, part of the visible hydrogen spectrum emitted as electrons, and protons recombine to form hydrogen atoms.

3. (p. 314) Because the cloud's main constituent, hydrogen, is very hard to observe, astronomers must use other molecules as tracers of the cloud's properties. 4. (p. 321) (1) The existence of a photosphere, meaning that the inner part of the cloud becomes opaque to its own radiation, signaling the slowing of the collapse phase. (2) Nuclear fusion in the core, and equilibrium between pressure and gravity. 5. (p. 322) No. Different parts of the main sequence correspond to stars of different masses. A typical star stays at roughly the same location on the main sequence most of its lifetime. 6. (p. 326) Because stars form at different rates—high-mass stars reach the main sequence and start disrupting the parent cloud long before lower-mass stars have finished forming.

Chapter 12

1. (p. 333) Hydrostatic equilibrium means that, if some property of the Sun changes a little, the star's structure adjusts to compensate. Small changes in the Sun's internal temperature or pressure will not lead to large changes in its radius or luminosity. 2. (p. 335) Because the nonburning inner core, unsupported by fusion, begins to shrink, releasing gravitational energy, heating the overlying layers, causing them to burn more vigorously, and increasing the luminosity. 3. (p. 341) No. It does not have a binary companion to provide mass after the Sun becomes a white dwarf, so our star will never become a nova or Type I supernova; it is too low in mass to become a Type II supernova. 4. (p. 344) Because iron cannot fuse to produce energy. As a result, no further nuclear reactions are possible, and the core's equilibrium cannot be restored. 4. (p. 347) Because the two types of supernova differ in their spectra and their light curves, making it impossible to explain them in terms of a single phenomenon. 5. (p. 354) Because a star cluster gives us a "snapshot" of stars of many different masses—but of the same age and initial composition—allowing us to directly test the predictions of the theory. 6. (p. 355) Because it is responsible for creating and dispersing all the heavy elements out of which we are made. In addition, it may also have played an important role in triggering the collapse of the interstellar cloud from which our solar system formed.

Chapter 13

1. (p. 362) No. Only Type II supernovae. According to theory, the rebounding central core of the original star becomes a neutron star. 2. (p. 364) Because (1) not all supernovae form neutron stars, (2) the emission is beamed and may not be observable from Earth, and (3) pulsars spin down and become too faint to observe after a few tens of millions of years. 3. (p. 309) Some X-ray sources are binaries containing accreting neutron stars, which may be in the process of being spun up to form millisecond pulsars. 4. (p. 372) They are energetic bursts of gamma rays, roughly uniformly distributed on the sky, occurring roughly once per day. They pose a challenge because they are very distant, and hence extremely luminous, but their energy comes from a region less than a few hundred kilometers across. 5. (p. 374) Its gravity becomes so strong that even light cannot escape, and it becomes a black hole. 6. (p. 379) In Newton's theory, gravity is a force that exists between all massive bodies. In relativity, the acceleration we call gravity is actually our perception of motion through a curved spacetime, whose curvature depends on the local density of material. Special relativity makes some quite counterintuitive predictions about the universe—for example, time dilation, length contraction, and the loss of simultaneity—which scientists initially found hard to accept. However, all of its predictions have been repeatedly verified in laboratory experiments, and many predictions of general relativity have been verified by astronomical observations. 7. (p. 382) Because the object would appear to take infinitely long to reach the event horizon, and its light would be infinitely redshifted by the time it got there. 8. (p. 384) By observing their gravitational effects on other objects, and from the X-rays emitted when matter falls into them.

Chapter 14

1. (p. 392) The Milky Way is the thin plane of the Galactic disk, seen from within. When our line of sight lies in the plane of the Galaxy, we see many stars blurring into a continuous band. In other directions we see darkness. 2. (p. 395) No, because even the brightest Cepheids are unobservable at distances of more than a kiloparsec or so through the obscuration of interstellar dust. 3. (p. 396) The debate involved the size and location of the "spiral nebulae," such as M31 in Andromeda. Today we know them as spiral galaxies, but at the time astronomers had insufficient data to determine their distances, and hence their sizes. Shapley thought that the spiral nebulae were small, relatively nearby objects contained within our Galaxy. Curtis argued that the nebulae were distant galaxies comparable in size to our own. Shapley used observations of variable stars to argue that our Galaxy is large; Curtis thought it was much smaller. In the end, neither scientist was completely right. Shapley was correct about the size of the Galaxy, but Curtis was right in his assertion that the spiral nebulae are distant galaxies like the Milky Way. The matter was resolved a few years later when Edwin Hubble used observations of variable stars to demonstrate that many spiral nebulae did indeed reside far outside our Galaxy. 4. (p. 399) They differ greatly in their spatial distributions of stars, the types and ages of stars found in each, the amount of interstellar gas they contain, and in the orbital motions of their component stars. 5. (p. 401) Because all the gas and dust in the halo fell to the Galactic disk billions of years ago, halo star formation has long since ceased. 6. (p. 402) Because differential rotation would destroy the spiral structure within a few hundred million years. 7. (p. 407) Scientists are unwilling to suggest new physics to explain observations, and competing theories of galactic rotation curves and "missing mass" on large scales do exist. However, despite their reservations, most astronomers have concluded that dark matter, introduced as material with gravity but no interaction with electromagnetic radiation, best fits the observed facts. Several theories exist to explain how dark matter might have been formed in the early universe, and they lead to experimental tests that should some day detect dark matter if it exists. 8. (p. 408) Its emission has not been observed at any electromagnetic wavelength. Its presence is inferred from its gravitational effect on stars and gas orbiting the Galactic center. 9. (p. 413) Observations of rapidly moving stars, gas, and the variability of the radiation emitted suggest the presence of a roughly 3 million-solar-mass black hole.

Chapter 15

1. (p. 425) Most galaxies are not large spirals—the most common galaxy types are dwarf ellipticals and dwarf irregulars. 2. (p. 426) Distance-measurement techniques ultimately rely upon the existence of very bright objects whose luminosities can be inferred by other means. Such objects become increasingly hard to find and calibrate the farther we look out into intergalactic space. 3. (p. 430) It doesn't use the inverse-square law. The other methods all provide a way of determining the luminosity of a distant object, which then is converted to a distance using the inverse-square law. Hubble's law gives a direct connection between redshift and distance. 4. (p. 433) Because it means that the energy source cannot simply be the summed energy of a huge number of stars—some other mechanism must be at work. 5. (p. 439) When quasars were discovered, they were thought to be faint, relative nearby stars, or starlike objects, although their unusual spectra posed problems for astronomers. Once astronomers realized that their odd spectra actually meant that they had very large redshifts, it became clear that quasars were actually among the most distant—and hence most luminous—objects in the entire universe. 6. (p. 440) The energy is generated in an accretion disk in the central nucleus of the visible galaxy, then transported by jets out of the galaxy and into the lobes, where it is eventually emitted by the synchrotron process in the form of radio waves.

Chapter 16

1. (p. 450) First, that the galaxies are gravitationally bound to the cluster. Second, and more fundamentally, that the laws of physics as we know them in the solar system—gravity, atomic structure, the Doppler effect—all apply on very large scales, and to systems possibly containing a lot of dark matter. 2. (p. 457) Galaxies in voids are much less likely to encounter other galaxies, so their evolution will be dictated more by "internal" processes—star formation and stellar evolution—than galaxies in clusters, which will be more affected by interactions with other galaxies. 3. (p. 457) The scenario makes predictions about how different types of galaxies were assembled over the history of the universe, and this has consequences for the types, compositions, and ages of the stars they contain. Astronomers can gauge the accuracy of the model by comparing its predictions with the properties of spiral and elliptical galaxies at different redshifts (that is, at different times in the past). 4. (p. 461) Astronomers think that the first black holes formed in young galaxies early in the history of the universe. The black holes grew by accretion of stars and gas from the surrounding galaxies, as well as mergers with other black holes when their parent galaxies merged. Eventually, they form the supermassive black holes observed in normal galaxies today. The galaxy mergers were often responsible for directing additional galactic gas onto the central black holes. The connection with active galaxies is that, during the periods of accretion, the black holes emitted large amounts of energy, becoming the active galactic nuclei we see. 5. (p. 462) Probably not. There may well be galaxies that do not harbor central black holes, and in any case, only galaxies in clusters are likely to experience the encounters that trigger activity. 6. (p. 464) Light traveling from these objects to Earth is influenced by cosmic structure all along the line of sight. Light rays are deflected by the gravitational field of intervening concentrations of mass, and gas along the line of sight produces absorption lines whose redshifts tell us the distance at which each feature formed. The light received on Earth thus gives astronomers a "core sample" through the universe, from which detailed information can be extracted.

Chapter 17

1. (p. 476) When viewed on very large scales—more than 300 Mpc—the distribution of galaxies seems to be roughly the same everywhere and in all

directions. (In addition, the microwave background radiation field is observed to be isotropic to very high precision.) 2. (p. 479) Because, tracing the motion backward in time, it implies that all galaxies, and in fact everything in the entire universe, were located at a single point at the same instant in the past. The cosmological principle does not allow that point to be special, leaving a Big Bang as the only possibility. 3. (p. 480) If there is enough matter in the universe for gravity to halt and reverse the current expansion, the universe will eventually recollapse in a "Big Crunch." Otherwise, the universe will expand forever. 4. (p. 481) A low-density universe has negative curvature and is infinite in extent; a critical-density universe is spatially flat (Euclidean) and is also infinite in extent; a high-density universe has positive curvature and is finite in extent. 5. (p. 485) The observed acceleration of the expansion of the universe implies that some nongravitational force must be at work. Dark energy is our current best theory of the cause of that force. In addition, galactic and cosmological observations indicate that the universe is spatially flat, and hence has critical density, but that the density of matter (mostly dark) cannot account for the total. The amount of dark energy needed to account for the cosmic acceleration is in good agreement with the required extra density—about 70 percent of the critical value. 6. (p. 487) There doesn't seem to be enough matter to halt the collapse, and in addition, the observed cosmic acceleration suggests the existence of a large-scale repulsive force in the cosmos that also opposes recollapse. 7. (p. 488) It was formed at the time of the Big Bang. It is the electromagnetic remnant of the primeval fireball. It started off as a blackbody curve because it was the thermal emission of the hot, young cosmos. It has retained this form because the cosmological redshift has stretched all photons by the same factor, preserving the shape of the blackbody curve. 8. (p. 490) The amount of deuterium observed in the universe today implies that the present density of normal matter is at most a few percent of the critical value—much less than the density of dark matter inferred from dynamical studies. 9. (p. 444) Not directly. Inflation implies that the universe is flat and hence that the total cosmic density equals the critical value. However, the matter density seems to be only about one-third of the critical value, and the density of electromagnetic radiation (the microwave background) is a tiny fraction of the critical density. Together, these statements suggest that the remaining density is in the form of "dark energy," as described in Section 17.3. 10. (p. 497) Because dark matter is largely unaffected by the background radiation field, it was able to clump earlier than normal matter, forming the structures within which luminous matter subsequently formed the galaxies we see today. The gravity of the early dark-matter clumps caused tiny fluctuations in the temperature of the cosmic microwave background. The ripples we see today in the microwave background are the beginning of galaxy formation long ago.

Chapter 18

1. (p. 508) Not yet. The formation of complex molecules from simple ingredients by nonbiological processes has been repeatedly demonstrated, but no living cell or self-replicating molecule has ever been created. 2. (p. 510) Mars remains the most likely site because of its generally Earthlike makeup and because several lines of evidence suggest that the planet was warmer in the past and may have had liquid water on its surface. Europa and Titan also have properties that might have been conducive to the emergence of living organisms—liquid water under Europa's icy crust and an atmosphere and many complex molecules on Titan. 3. (p. 516) It breaks a complex problem up into simpler "astronomical," "biochemical," "anthropological," and "cultural" pieces, which can be analyzed separately. The analysis itself helps identify the types of stars where a search might be most fruitful. 4. (p. 517) We assume that a technological civilization will opt to work in the radio part of the spectrum, where Galactic absorption is least, and will choose a region where natural Galactic background "static" is minimized. We also assume that the 21-cm line of hydrogen will have significance to them, since hydrogen is the most common element in the universe, and that hydroxyl will also have special meaning if they evolved in a water environment as we did.

Answers to Self-Test Questions

Chapter 0

True or False?/Multiple Choice 1) F 2) F 3) T 4) F 5) T 6) T 7) F 8) b 9) b 10) c 11) a 12) c 13) d 14) b 15) a

Problems 1) Scorpius 2) 29.9 km, 1.08×10^5 km, 2.58×10^6 km 3) It would decrease by 8 minutes 4) (a) 33 arc minutes, (b) 33 arc seconds, (c) 0.55 arc seconds; 56.4 minutes 5) 1.0 km/s 6) It is! 7) 173 m 8) (a) 57,300 km, (b) 3.44×10^6 km, (c) 2.06×10^8 km 9) 2.9°

Chapter 1

True or False?/Multiple Choice 1) F 2) F 3) F 4) F 5) F 6) F 7) F 8) T 9) d 10) c 11) c 12) a 13) c 14) b 15) b

Problems 1) (a) 110 km, (b) 44,000 km, (c) 370,000 km 2) 700 s 3) 0.4 degrees retrograde 4) 3 AU, 0.333, 5.2 yr 5) 35 AU 6) Mercury's perihelion and aphelion distances are 0.307 AU and 0.467 AU, respectively. The difference is 0.159 AU. Alternatively, Mercury's aphelion distance is 52 percent larger than the perihelion distance. 7) 9.42×10^{-4} solar = 1.88×10^{27} kg 8) 9.50, 7.33, 1.49 m/s^2 9) For a 70-kg person, force = 684 N = 154 pounds; we call it the person's weight 10) 1.7 km/s

Chapter 2

True or False?/Multiple Choice 1) F 2) T 3) T 4) F 5) T 6) T 7) T 8) a 9) d 10) a 11) b 12) c 13) d 14) a 15) d

Problems 1) 1480 m/s 2) 3 m 3) 23 Hz; radio 4) A; 3.25; 112 5) 310; 9.4 microns; infrared 6) 6.4×10^7 W/m^2; 3.9×10^{26} W 7) 3×10^{10} 8) Second excited state: 3 possibilities: $2 \rightarrow 1$ (Hα, 656 nm), $2 \rightarrow$ ground (Lyβ, 103 nm), $1 \rightarrow$ ground (Lyα, 122 nm); Third excited state: 6 possibilities: those already listed, plus $3 \rightarrow 2$ (called Paschen α, 1876 nm), $3 \rightarrow 1$ (Hβ, 486 nm), $3 \rightarrow$ ground (Lyγ, 97.3 nm) 9) 137 km/s approaching 10) 1.94×10^{27} kg

Chapter 3

True or False?/Multiple Choice 1) F 2) F 3) T 4) T 5) F 6) F 7) F 8) d 9) d 10) c 11) a 12) d 13) b 14) b 15) c

Problems 1) 0.3 arc seconds; 6.8 pixels 2) 580 μm; longer than the 3 – 200 μm operating range 3) 6.7 minutes; 1.7 minutes 4) (a) 0.25″, (b) 0.01″ 5) 15 m 6) 160 light-years, using the formula in the text to compute the resolution 7) 3.3 minutes 8) (a) 36, (b) 0.61, (c) 0.012 light-years 9) 14.1 m, 16 m 10) (a) 0.003 arc seconds, (b) 0.005 arc seconds

Chapter 4

True or False?/Multiple Choice 1) F 2) T 3) F 4) F 5) F 6) T 7) F 8) d 9) b 10) d 11) a 12) c 13) b 14) a 15) c

Problems 1) 2×10^{21} kg, 0.03 percent of Earth's mass; 40 km 2) 1.1 AU, 2.0 AU 3) 3 kg 4) 1, 0.1, 0.01, 0.001 times Ceres's mass, or 1.6×10^{21} kg, 1.6×10^{20} kg, 1.6×10^{19} kg, 1.6×10^{18} kg. 5) (a) 11 million years, (b) 50 AU 6) The orbital period is 0.00836 years = 3.05 days, so (for example) January 1, 2013, would be $14 \times 365 + 4$ (leap days) + 31 = 5145 days = 1685 periods after discovery. 7) 1.7, 0.8 Earth gravity 8) 890 AU 9) 2×10^8; once every 2.5 years 10) 0.25 AU

Chapter 5

True or False?/Multiple Choice 1) T 2) T 3) T 4) F 5) T 6) F 7) F 8) b 9) d 10) b 11) b 12) d 13) d 14) a 15) c

Problems 1) 5.3 m/s^2 = 0.55 times the actual value, 8.3 km/s 2) 30 kg 3) 21 m = 70 feet 4) 1.6×10^{-7} 5) (a) 8.4×10^{-3}, (b) 0.16, (c) 0.84, (d) 7.0×10^{-3} times Earth's mass 7) 45 percent 8) 43 minutes 9) Need at least 4.8×10^5 such craters, requiring at least 4.8 trillion years; rate must have been greater by a factor of about 1000 10) 93 m

Chapter 6

True or False?/Multiple Choice 1) T 2) F 3) T 4) T 5) T 6) F 7) F 8) b 9) b 10) d 11) c 12) b 13) b 14) a 15) c

Problems 1) 8.8 minutes 2) 4.0×10^{23} kg, (for a temperature of 700 K) or roughly 22 percent greater than it is now 3) 4.9×10^{20} kg, 98 times more massive than Earth's atmosphere, 10^{-4} times the mass of Venus 4) 400 km/h, 250 mph 5) (a) 12,100 km, (b) yes—the smallest detectable feature would be about 20 km across, much smaller than the largest impact features 6) 197 minutes, 94 minutes 7) 28 kg, assuming I weigh 70 kg on Earth 8) 10 m/s = 22 mph 9) 2.7×10^{17} kg; 4.5×10^{-7} times the mass of Mars; 5.5×10^{-4} times the mass of Venus's atmosphere 10) 16′, 2.7′; no—the minimum angular diameter of the Sun, as seen from Mars, is 19′

Chapter 7

True or False?/Multiple Choice 1) F 2) T 3) F 4) T 5) T 6) F 7) T 8) T 9) a 10) d 11) d 12) b 13) c 14) a 15) b

Problems 1) 150 km, or 0.002 planetary radii; 1100 km, or 0.04 planetary radii 2) 2.2×10^{17} newton; 1.4×10^{21} newton, or 6400 times larger 3) 4200 s = 1.17 hours; 84,000 km 4) 6×10^{-5} Jupiter masses, or 0.019 Earth masses 5) — 6) 1.5 percent of the actual mass 7) 10.5 days 8) 74 K 9) 1.7×10^{25} kg (2.8 Earth masses); 81 percent 10) 49 μm; infrared

Chapter 8

True or False?/Multiple Choice 1) T 2) T 3) T 4) T 5) F 6) T 7) T 8) F 9) a 10) c 11) c 12) b 13) d 14) c 15) b

Problems 1) 20.3 km/s, 7.6 km/s; Saturn is much more massive than Earth! 2) 2.3 Jupiter radii 3) For Io: acceleration difference = 6.3×10^{-3} m/s^2, surface gravity = 1.8 m/s^2, ratio = 0.0035 = 0.35 percent; For Moon: acceleration difference = 2.2×10^{-5} m/s^2, surface gravity = 1.6 m/s^2, ratio = 1.4×10^{-5} 4) 1.35 m/s^2 (Earth: 9.80 m/s^2); 5) 2.6 km/s Io: 36′, Europa: 18′, Ganymede: 18′, Callisto: 9′, Sun: 6′; Yes 6) 38 km radius 7) 1.1×10^{18} 8) 6.8 times farther out 9) For a weight of 70 kg, 4.7 kg on Pluto, 2.1 kg on Charon 10) 11.1 hours; 28.700 km; 2.8 orbits

Chapter 9

True or False?/Multiple Choice 1) T 2) F 3) F 4) F 5) T 6) F 7) F 8) c 9) c 10) a 11) b 12) c 13) a 14) b 15) c

Problems 1) (a) 14,600 W/m^2; (b) 52 W/m^2 2) (a) 3000 km, (b) 1500, (c) 1/33 of the 167-minute orbital period 3) (a) 0.29 nm (hard X-ray), (b) 29 nm (far UV), (c) 290 nm (near UV) 4) 100 s = 17 min, comparable to the granule lifetime 5) 36 percent of the average solar value (64 percent less) 6) (a) radiation mass loss = 4.3 million tons/s ≈ twice the mass loss due to the solar wind; (b) 30 trillion years 7) 83 days 8) 300,000 years 9) 74 billion years 10) 4×10^{28}

Chapter 10

True or False?/Multiple Choice 1) F 2) F 3) F 4) F 5) T 6) F 7) T 8) d 9) b 10) b 11) c 12) d 13) c 14) b 15) b

Problems 1) 77 pc; 0.39″ 2) 47 km/s; 56 km/s 3) (a) 80 times the luminosity of the Sun; (b) 2 solar radii 4) B is 3 times farther away 5) A is 10 times farther away 6) 3.3×10^{-10} W/m^2; 2.3×10^{-13} times the solar constant 7) factor of 16 trillion 8) 320 pc 9) 3.5, 2.3 solar masses 10) (a) 200 billion years, (b) 1 billion years, (c) 100 million years

Chapter 11

True or False?/Multiple Choice 1) F 2) F 3) F 4) F 5) F 6) T 7) T 8) d 9) b 10) c 11) d 12) b 13) b 14) c 15) b

Problems 1) 1.9 grams 2) 1428.6 MHz for a wavelength of 21 cm (but note that the precise wavelength is 21.11 cm, corresponding to frequency of 1420.4 MHz); frequency: 1428.8–1428.2 MHz, wavelength: 20.9965–21.0053 cm 3) 0.017 pc = 3500 AU 4) 4100, 9.0 5) escape speeds (km/s): 1.8, 1.1, 1.1, 0.80; average molecular speeds: 13.6, 14.0, 14.6, 14.2; No 6) yes, barely: the escape speed is 0.93 km/s, molecular speed is 0.35 km/s 7) (a) 200, (b) 2.3 solar radii 8) 8 9) 10^{-6} solar luminosities 10) 37 pc

Chapter 12

True or False?/Multiple Choice 1) T 2) T 3) F 4) T 5) F 6) T 7) T 8) F 9) a 10) b 11) a 12) b 13) b 14) c 15) d

Problems 1) 3.5×10^7 kg/m^3; 5.7×10^{-4} kg/m^3, smaller by a factor of 1.6×10^{-11}; solar central density is 150,000 kg/m^3, smaller than the white dwarf density by a factor of 4.3×10^{-3} 2) 220 pc 3) (a) 2.9 solar masses, (b) 1.7 solar masses 4) 7.1 years, 63,000 years 5) 7300 km/s, 500,000 Earth gravities 6) 20, 3.2 Mpc; 1000 Mpc 7) 0.4 pc; no—there are no O or B stars (in fact no stars at all) within that distance of the Sun 8) apparent magnitude is –14.1, 1.6 magnitudes (4 times) brighter than the full Moon, 9.7 magnitudes (7600 times) brighter than Venus; yes—according to Appendix 3, several O and B stars, as well as Betelgeuse and some other red supergiants, lie within that distance 9) roughly 1000 km/s; not too bad an assumption—the Nebula is moving too fast to be affected much by gravity, although it is probably slowing down as it runs into the interstellar medium 10) 1.2×10^{44} J; 220 Earth masses

Chapter 13

True or False?/Multiple Choice 1) T 2) T 3) T 4) F 5) T 6) F 7) F 8) b 9) a 10) b 11) c 12) b 13) c 14) c 15) b

Problems 1) 1 million revolutions per day, or 11.6 revolutions per second 2) 3×10^{44} times higher—2.1×10^{16} kg for a 70-kg human; Moon's mass is greater by a factor of 3.5 million; asteroid mass is roughly 1.6×10^{12} kg (assuming spherical shape and density 3000 kg/m^3), smaller by a factor of 13,000 3) 1.9×10^{12} m/s^2 or 190 billion Earth gravities; 190,000 km/s, or 64 percent of the speed of light; 300,000 km/s 4) 1.6×10^{-5}, 1.6×10^{3}, 1.6×10^{11} solar luminosities; ultraviolet, X-rays, gamma rays; they might be very bright immediately after formation, but would become very faint as they cool; the coolest could be plotted at the bottom left of the diagram, as a very faint O-type "star" 5) 2.4×10^{44} J, roughly twice the Sun's lifetime energy output; 2.4×10^{34} J; 1.4×10^{25} J 6) 140 μs 7) 3 million km = 4.3 solar radii; 3 billion km = 20 AU 8) 2×10^{10} m/s^2 = 2×10^{9} g; 2×10^{-3} g; 2×10^{-9} g 9) 1760 km 10) 3×10^{7} km = 0.2 AU

Chapter 14

True or False?/Multiple Choice 1) T 2) T 3) F 4) F 5) F 6) T 7) F 8) T 9) b 10) c 11) a 12) b 13) d 14) b 15) c

Problems 1) 2.0″, much less than the angular diameter of Andromeda 2) 100 kpc 3) 10 times 4) − 6.2; 17 Mpc 5) 0.014″/yr; proper motion has in fact been measured for several globular clusters 6) 2.7×10^{11} solar masses 7) 570 million years 8) 18 9) 1 kpc 10) 1600 AU, 2.6×10^{6} solar masses

Chapter 15

True or False?/Multiple Choice 1) F 2) T 3) T 4) T 5) T 6) T 7) T 8) a 9) c 10) b 11) b 12) a 13) b 14) c 15) c

Problems 1) 3 billion years 2) 17 Mpc, taking the luminosity of the Cepheid to be 10^{4} times that of the Sun 3) 320 Mpc 4) 14,000 km/s, 57 Mpc; 10,000 km/s, 80 Mpc; 16,000 km/s, 50 Mpc 5) 14 billion years; 14 billion years 6) 1.8×10^{8} solar masses 7) 1.1 million years 8) 1.3×10^{36} W = 3.2 billion solar luminosities 9) 7200 km/s 10) Seyfert: ; Sirius A: ; smaller by a factor of 120; yes, if much of the emission from the nucleus is in the infrared

Chapter 16

True or False?/Multiple Choice 1) F 2) F 3) F 4) T 5) T 6) F 7) T 8) T 9) b 10) c 11) d 12) a 13) d 14) b 15) a

Problems 1) 1.2×10^{12} solar masses 2) 5.6×10^{11} solar masses, assuming a velocity of 350 km/s 3) 9.3×10^{10} solar masses 4) 700 km/s, comparable to the 660 km/s speed of the galaxy in the cluster 5) 130 million years 6) −27.2; 6.4 trillion solar luminosities; apparent magnitude of the Sun = −26.8; so the quasar at 10 pc is 0.4 magnitudes, or a factor of 1.4 times, brighter than the Sun at 1 AU 7) − 22.5; 8.3×10^{10} solar luminosities 8) 11 million years 9) 21 Mpc 10) 48 kpc

Chapter 17

True or False?/Multiple Choice 1) F 2) F 3) F 4) T 5) T 6) F 7) T 8) T 9) a 10) d 11) c 12) d 13) b 14) c 15) a

Problems 1) 1000 Mpc 2) 4×10^{8} 3) 1200 km/s, directly away from the opposite corner 4) 20, 14, 12 billion years 5) (a) 30,000 tons, (b) 2.8 pc 6) 3×10^{15} solar masses; 1200 km/s 7) (a) 1.1 mm, (b) 0.0093, (c) 9.3×10^{-5}, (d) 9.3×10^{-7} 8) 9×10^{-18} kg/m^3; 5×10^{-19} kg/m^3 9) 91 kpc 10) 74 kpc

Chapter 18

True or False?/Multiple Choice 1) F 2) F 3) T 4) F 5) T 6) T 7) T 8) b 9) c 10) c 11) b 12) d 13) a 14) d 15) d

Problems 1) 6.3 seconds (for a 20-year-old reader); 18 seconds (in 2003); 72 seconds; 161 seconds; 237 days 2) 0.19–0.47 AU 3) 5 billion 4) 27 AU 5) (a) 0.2, (b) 20, (c) 2000 6) 3100 years, 3.1 million years 7) 32,000 km/s 8) 5×10^{8} W, 500 times the emission of the Sun 9) 1.43×10^{9} to 1.67×10^{9} Hz; 2.4×10^{6} channels 10) 2.3 years; 55 years

Credits

Chapter 0

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Chapter 2

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Chapter 3

Opener European Southern Observatory **3.6a** W.M. Keck Observatory **3.6c** W.M. Keck Observatory **p. 76** NASA **p. 77** ESO **3.7a** MIT Lincoln Lab **3.7b** National Optical Astronomy Observatory (NOAO) **3.8a** NASA **3.8b** NASA **3.8c** NASA **3.8d** Association of Universities for Research in Astronomy, Inc. **3.9a** Association of Universities for Research in Astronomy, Inc. **3.9b** Association of Universities for Research in Astronomy, Inc. **3.10a** Richard J. Wainscoat/Aina Kai LLC **3.10b** National Astronomical Observatory of Japan **3.11** European Southern Observatory **3.12a** Association of Universities for Research in Astronomy, Inc. **3.12b** Association of Universities for Research in Astronomy, Inc. **3.12c** Association of Universities for Research in Astronomy, Inc. **3.12d** Association of Universities for Research in Astronomy, Inc. **3.14a** European Southern Observatory **3.14b** European Southern Observatory **3.15a** Laurie Hatch Photography **3.15b** National Radio Astronomy Observatory (NRAO) **3.15c** National Radio Astronomy Observatory (NRAO) **3.16a** National Radio Astronomy Observatory (NRAO) **3.17a** National Astronomy and Ionosphere Center **3.17b** Tony Acevedo/National Astronomy and Ionosphere Center **3.17c** National Astronomy and Ionosphere Center **3.18** Dr. Jack O.Burns **3.19a** National Radio Astronomy Observatory Headquarters **3.19b** National Radio Astronomy Observatory Headquarters **3.21a** ESO **3.21b** ESO **3.22a** ALMA (ESO/NAOJ/NROA) **3.22b** NASA, ESA and the Hubble Heritage Team (STScI/ AURA)-ESA/Hubble Collaboration **3.23a** Smithsonian Astrophysical Observatory **3.24a** Lick Observatory Publications Office **3.24b** Lick Observatory Publications Office **3.24c** NASA **3.24d** NASA **3.25a** NASA Jet Propulsion Laboratory **3.25b** NASA Jet Propulsion Laboratory **3.26a** NASA **3.26b** Galex/NASA Johnson Space Center **3.27c** NASA **3.28** NASA/CXC/SAO **3.29** NASA/DOE/Fermi LAT Collaboration, Tom Bash and John Fox/Adam Block/NOAO/AURA/NSF, JPL-Caltech/UCLA **3.30c** Axel Mellinger **p. 97** Association of Universities for Research in Astronomy Inc. **p. 97** National Radio Astronomy Observatory

Chapter 4

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Chapter 5

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Chapter 6

Opener NASA **6.1b** Science Source **6.2** Palomar Observatory **6.5** National Optical Astronomy Observatories **6.6** Observatorie du Pic due Midi **6.8a** NASA **6.8b** NASA/ ESA **6.9** Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington/NASA **6.10** Johns Hopkins University Applied Physics Laboratory/ Carnegie Institution of Washington/NASA **6.11** NASA Jet Propulsion Laboratory **6.12** NASA **6.13a** NASA **6.13b** NASA **6.14** NASA **6.15a** NASA **6.15b** NASA **6.15c** NASA **6.16** NASA **6.17** Russian Space Agency **6.18a** NASA **6.18b** NASA **p. 180 (left)** Lowell Observatory **p. 180 (right)** Lowell Observatory **p. 188 (left)** NASA **p. 188 (right)** NASA **6.19** NASA **6.20a** NASA/JPL-Caltech/Univ. of Arizona **6.20b** NASA/JPL-Caltech/Univ. of Arizona **6.22** NASA **6.23a** NASA/JPL-Caltech/ Univ. of Arizona **6.23b** NASA **6.24** NASA **6.25** NASA **6.26a** NASA **6.26b** NASA **6.27** NASA Goddard Space Flight Center **6.28** NASA/JPL-Caltech/Univ. of Arizona **6.29a** NASA **6.29b** NASA **6.30** NASA **p. 189 (center)** NASA **p. 189 (right inset)** NASA **p. 189 (left inset)** NASA **6.31** NASA **6.31 (inset)** NASA **6.32a** JPL-Caltech/ Malin Space Science Systems/NASA **6.32b** JPL-Caltech/MSSS/NASA Jet Propulsion Laboratory **p. 196** NASA **p. 196** Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington/NASA **p. 196** NASA **p. 196** NASA/ JPL-Caltech/Univ. of Arizona **p. 196** NASA

Chapter 7

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Chapter 8

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Chapter 9

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Chapter 10

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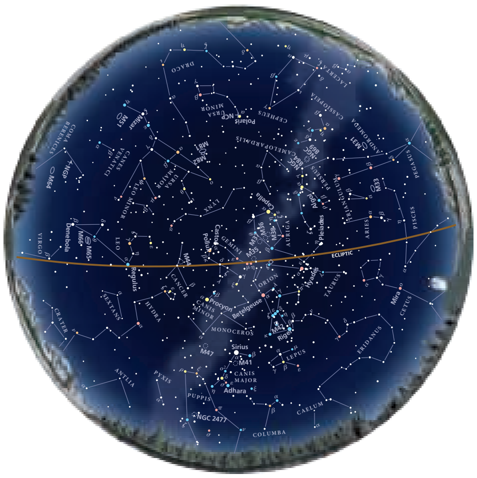
Star Charts

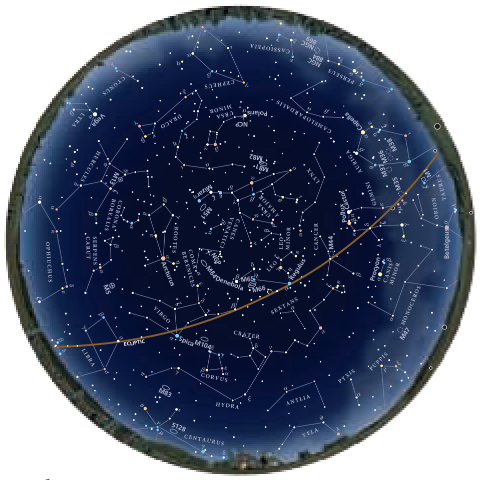
Have you ever become lost in an unfamiliar city or state? Chances are you used two things to get around: a map and some signposts. In much the same way, these two items can help you find your way around the night sky in any season. Fortunately, in addition to the seasonal Star Charts on the following pages, the sky provides us with two major signposts. Each seasonal description will talk about the Big Dipper—a group of seven bright stars that dominates the constellation Ursa Major the Great Bear. Meanwhile, the constellation Orion the Hunter plays a key role in finding your way around the sky from late autumn until early spring.

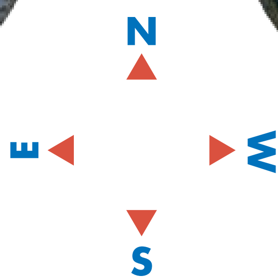
Each chart portrays the sky as seen from near 35° north latitude at the times shown at the top of the page. Located just outside the chart are the four directions: north, south, east, and west. To find stars above your horizon, hold the map overhead and orient it so a direction label matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

WINTER

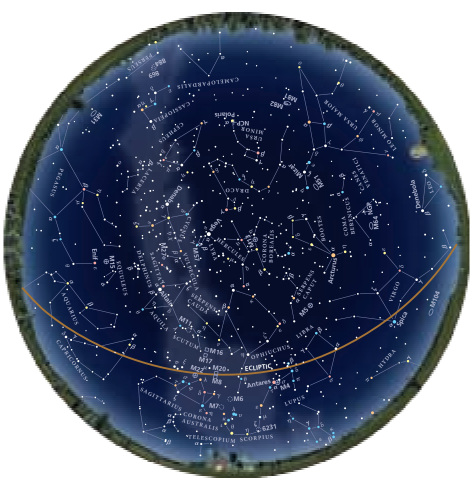


SPRING

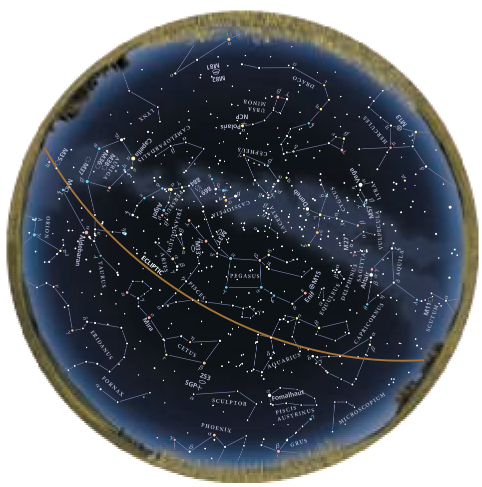




SUMMER



AUTUMN



Exploring the Winter Sky

Winter finds the Big Dipper climbing the northeastern sky, with the three stars of its handle pointing toward the horizon and the four stars of its bowl standing highest. The entire sky rotates around a point near Polaris, a second-magnitude star found by extending a line from the uppermost pair of stars in the bowl across the sky to the left of the Dipper. Polaris also performs two other valuable functions: The star's altitude above the horizon equals your latitude north of the equator, and a vertical line dropped from Polaris to the horizon indicates the direction of true north.

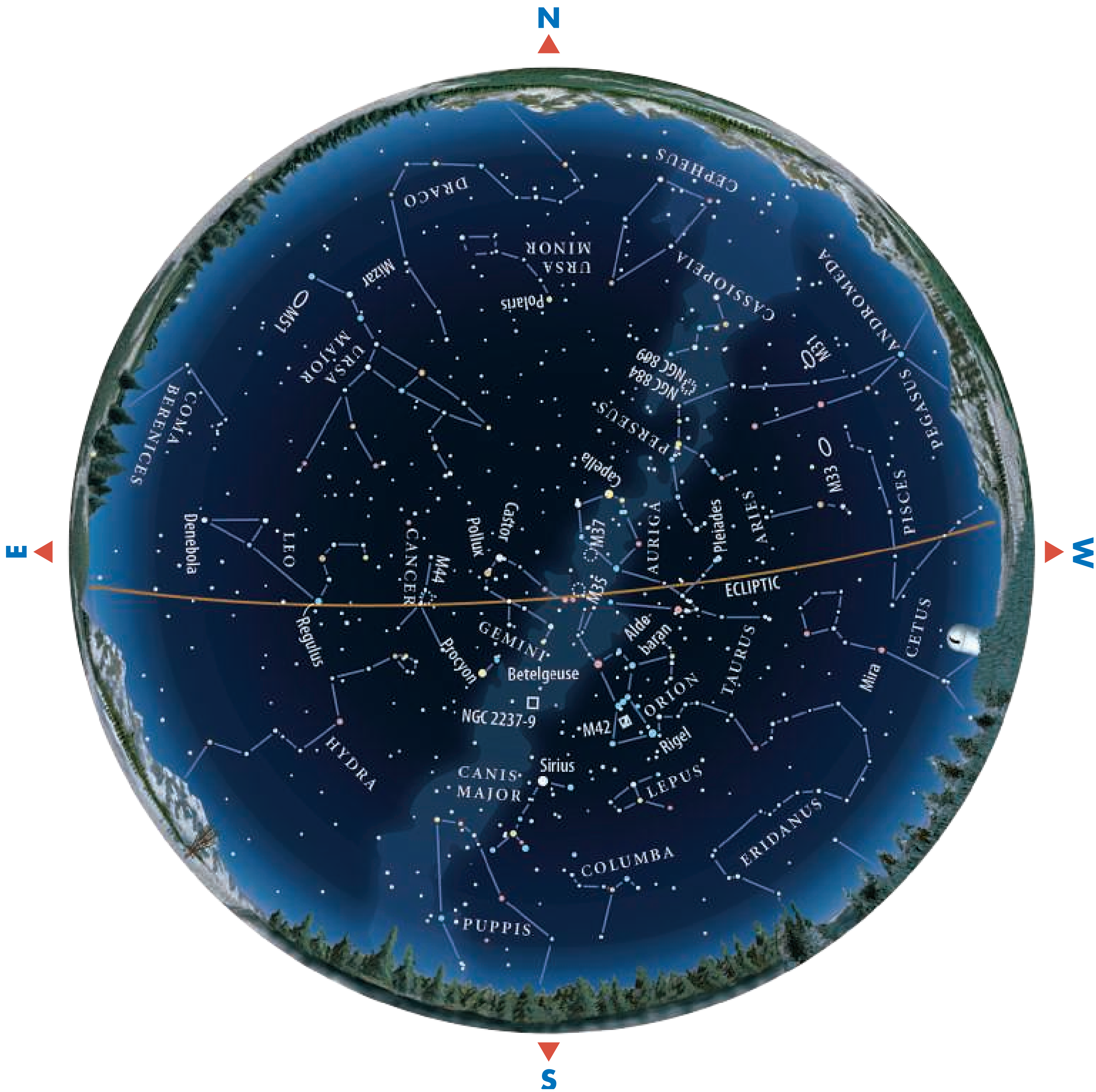
Turn around with your back to the Dipper and you'll be facing the diamond-studded winter sky. The second great signpost in the sky, Orion the Hunter, is central to the brilliant scene. Three closely spaced, second-magnitude stars form a straight line that represents the unmistakable belt of Orion. Extending the imaginary line joining these stars to the upper right leads to Taurus the Bull and its orangish first-magnitude star, Aldebaran. Reverse the direction of your gaze to the belt's lower left and you cannot miss Sirius the Dog Star—brightest in all the heavens at magnitude –1.5.

Now move perpendicular to the belt from its westernmost star, Mintaka, and find at the upper left of Orion the red supergiant star Betelgeuse. Nearly a thousand times the Sun's diameter, Betelgeuse marks one shoulder of Orion. Continuing this line brings you to a pair of bright stars, Castor and Pollux. Two lines of fainter stars extend from this pair back toward Orion—these represent Gemini the Twins. At the northeastern corner of this constellation lies the beautiful open star cluster M35. Head south of the belt instead and your gaze will fall on the blue supergiant star Rigel, Orion's other luminary.

Above Orion and nearly overhead on winter evenings is brilliant Capella, in Auriga the Charioteer. Extending a line through the shoulders of Orion to the east leads you to Procyon in Canis Minor, the Little Dog. Once you have these principal stars mastered, using the chart to discover the fainter constellations will be a whole lot easier. Take your time, and enjoy the journey. Before leaving Orion, however, aim your binoculars at the line of stars below the belt. The fuzzy "star" in the middle is actually the glorious Orion Nebula (M42), a stellar nursery illuminated by bright, newly formed stars.

WINTER

2 A.M. on December 1; midnight on January 1; 10 P.M. on February 1



Exploring the Spring Sky

The Big Dipper, our signpost in the sky, swings high overhead during the spring and lies just north of the center of the chart. This season of rejuvenation encourages us to move outdoors with the milder temperatures, and with the new season a new set of stars beckons us.

Follow the arc of stars outlining the handle of the Dipper away from the bowl and you will land on brilliant Arcturus. This orangish star dominates the spring sky in the kite-shaped constellation Boötes the Herdsman. Well to the west of Boötes lies Leo the Lion. You can find its brightest star, Regulus, by using the pointers of the Dipper in reverse. Regulus lies at the base of a group of stars shaped like a sickle or backward question mark, which represents the head of the lion.

Midway between Regulus and Pollux in Gemini, which is now sinking in the west, is the diminutive group Cancer the Crab. Centered in this group is a hazy patch of light that binoculars reveal as the Beehive star cluster (M44).

To the southeast of Leo lies the realm of the galaxies and the constellation Virgo the Maiden. Virgo's brightest star, Spica, shines at magnitude 1.0.

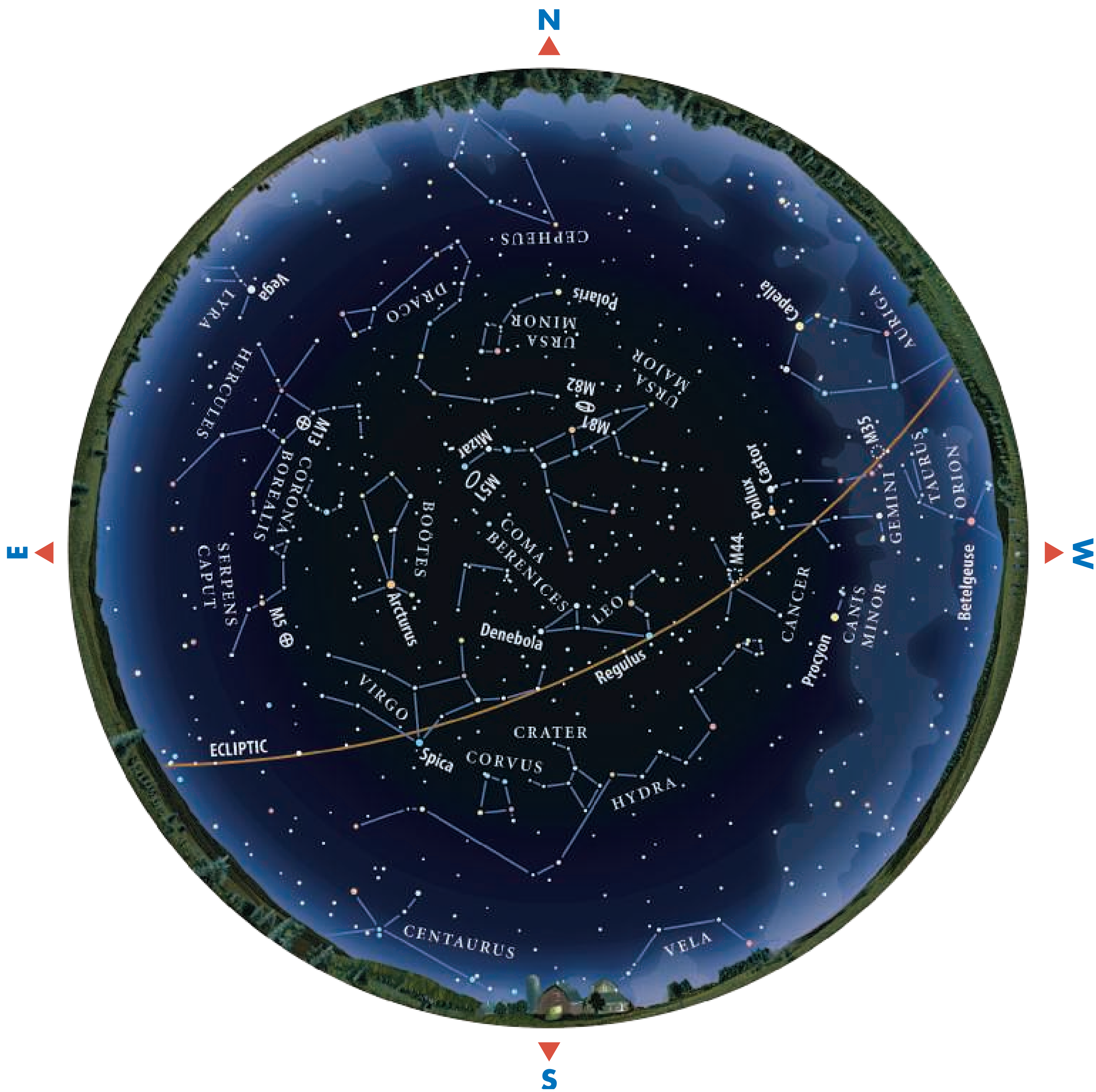
During springtime, the Milky Way lies level with the horizon, and it's easy to visualize that we are looking out of the plane of our Galaxy. In the direction of Virgo, Leo, Coma Berenices, and Ursa Major lie thousands of galaxies whose light is unhindered by intervening dust in our own Galaxy. However, all these galaxies are elusive to the untrained eye and require binoculars or a telescope to be seen.

Boötes lies on the eastern border of this galaxy haven. Midway between Arcturus and Vega, the bright "summer" star rising in the northeast, is a region where no star shines brighter than second magnitude. A semicircle of stars represents Corona Borealis the Northern Crown, and adjacent to it is a large region that houses Hercules the Strongman, the fifth-biggest constellation in the sky. It is here we can find the northern sky's brightest globular star cluster, M13. A naked-eye object from a dark site, it looks spectacular when viewed through a telescope.

Returning to Ursa Major, check the second-to-last star in the Dipper's handle. Most people will see it as double, and binoculars show this easily. The pair is called Mizar and Alcor, and they lie just 0.2° apart. A telescope reveals Mizar itself to be a double. Its companion star shines at magnitude 4.0 and lies 14 arcseconds away.

SPRING

1 A.M. on March 1; 11 P.M. on April 1; 9 P.M. on May 1. Add 1 hour for daylight-saving time



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Exploring the Summer Sky

The richness of the summer sky is exemplified by the splendor of the Milky Way. Stretching from the northern horizon in Perseus, through the cross-shaped constellation Cygnus overhead, and down to Sagittarius in the south, the Milky Way is packed with riches. These riches include star clusters, nebulae, double stars, and variable stars.

Let's start with the Big Dipper, our perennial signpost, which now lies in the northwest with its handle still pointing toward Arcturus. High overhead, and the first star to appear after sunset, is Vega in Lyra the Harp. Vega forms one corner of the summer triangle, a conspicuous asterism of three stars. Near Vega lies the famous double-double, Epsilon (ε) Lyrae. Two fifth-magnitude stars lie just over 3 arcminutes apart and can be split when viewed through binoculars. Each of these two stars is also double, but you need a telescope to split them.

To the east of Vega lies the triangle's second star: Deneb in Cygnus the Swan (some see a cross in this pattern). Deneb marks the tail of this graceful bird, the cross represents its outstretched wings, and the base of the cross denotes its head, which is marked by the incomparable double star Albireo. Albireo matches a third-magnitude yellow star and a fifth-magnitude blue star and offers the finest color contrast anywhere in the sky. Deneb is a supergiant star that pumps out as much light as 60,000 Suns. Also notice that the Milky Way splits into two parts in Cygnus, a giant rift caused by interstellar dust blocking starlight from beyond.

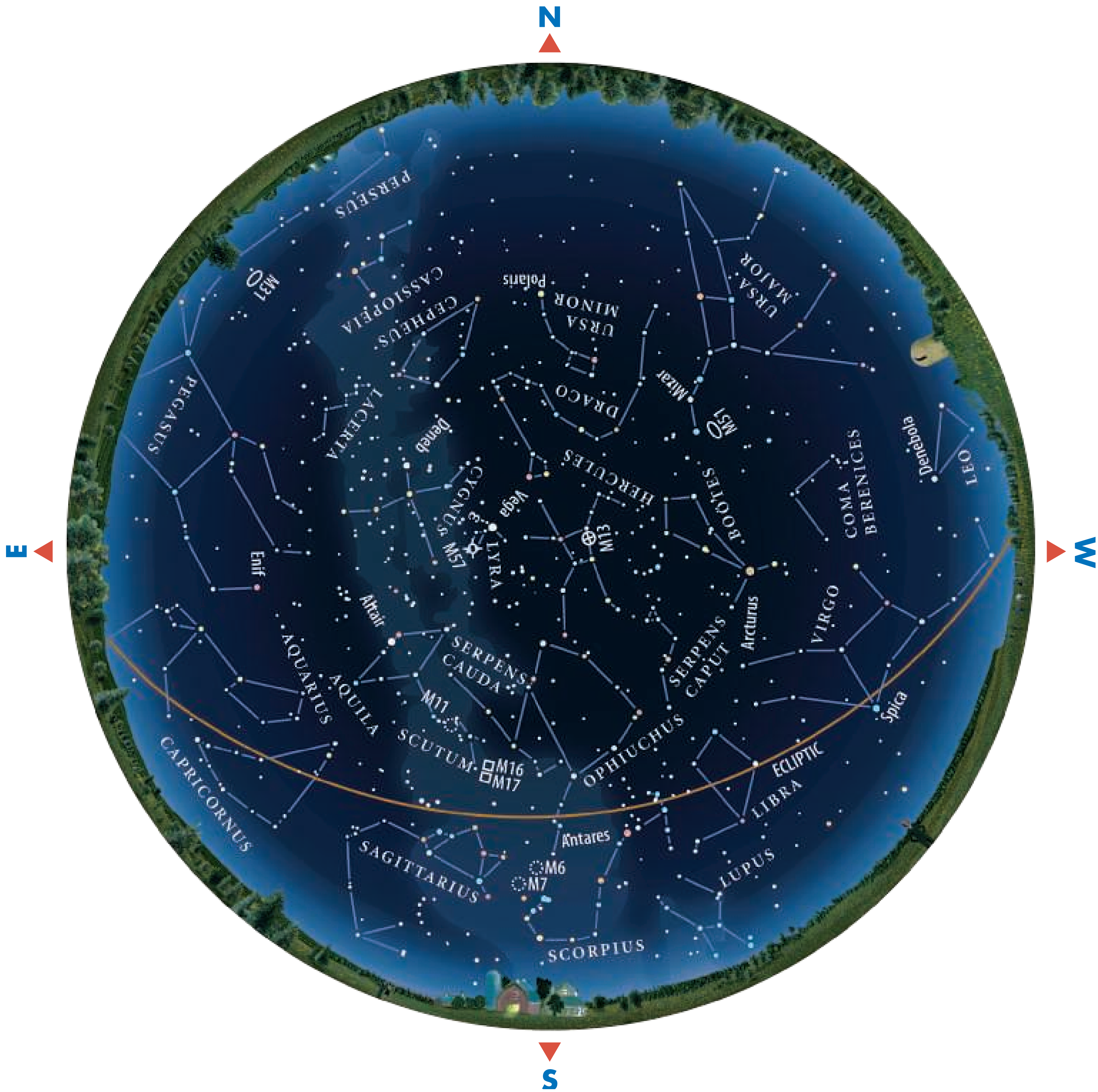
Altair, the third star of the summer triangle and the one farthest south, is the second brightest of the three. Lying 17 light-years away, it's the brightest star in the constellation Aquila the Eagle.

Frequently overlooked to the north of Deneb lies the constellation Cepheus the King. Shaped rather like a bishop's hat, the southern corner of Cepheus is marked by a compact triangle of stars that includes Delta (Δ) Cephei. This famous star is the prototype of the Cepheid variable stars used to determine the distances to some of the nearer galaxies. It varies regularly from magnitude 3.6 to 4.3 and back again with a 5.37-day period.

Hugging the southern horizon, the constellations Sagittarius the Archer and Scorpius the Scorpion lie in the thickest part of the Milky Way. Scorpius's brightest star, Antares, is a red supergiant star whose name means "rival of Mars" and derives from its similarity to the planet in both color and brightness.

SUMMER

1 A.M. on June 1; 11 P.M. on July 1; 9 P.M. on August 1. Add 1 hour for daylight-saving time



Exploring the Autumn Sky

The cool nights of autumn are here to remind us the chill of winter is not far off. Along with the cool air, the brilliant stars of the summer triangle descend in the west to be replaced with a rather bland-looking region of sky. But don't let initial appearances deceive you. Hidden in the fall sky are gems equal to summertime.

The Big Dipper swings low this season, and for parts of the Southern United States it actually sets. Cassiopeia the Queen, a group of five bright stars in the shape of a "W" or "M," reaches its highest point overhead, the same spot the Big Dipper reached 6 months ago. To the east of Cassiopeia, Perseus the Hero rises high. Nestled between these two groups is the wondrous Double Cluster—NGC 869 and NGC 884—a fantastic sight in binoculars or a low-power telescope.

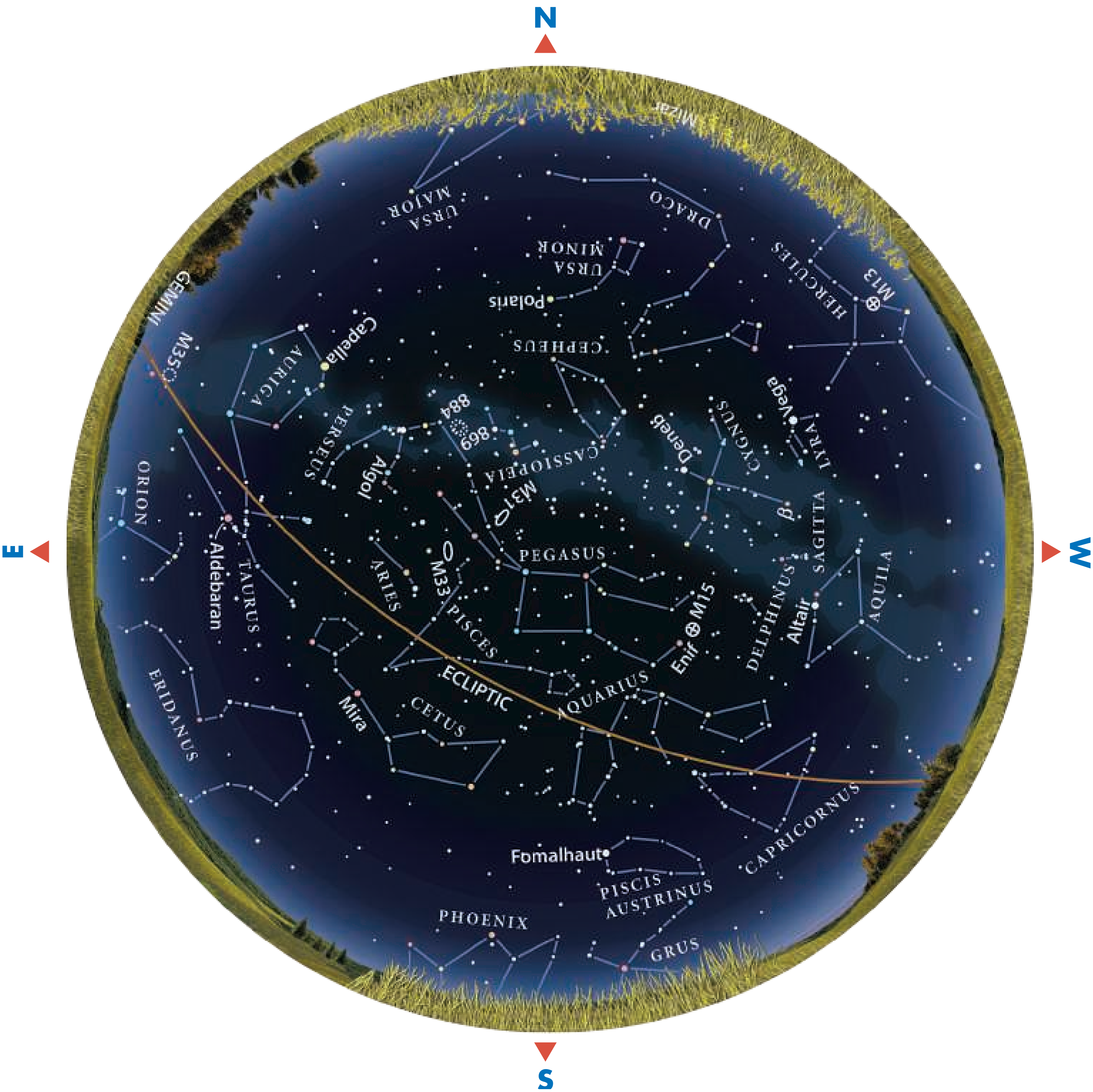
Our view to the south of the Milky Way is a window out of the plane of our Galaxy in the opposite direction to that visible in spring. This allows us to look at the Local Group of galaxies. Due south of Cassiopeia is the Andromeda Galaxy (M31), a fourth-magnitude smudge of light that passes directly overhead around 9 p.m. in mid-November. Farther south, between Andromeda and Triangulum, lies M33, a sprawling face-on spiral galaxy best seen in binoculars or a rich-field telescope.

The Great Square of Pegasus passes just south of the zenith. Four second- and third-magnitude stars form the square, but few stars can be seen inside of it. If you draw a line between the two stars on the west side of the square and extend it southward, you'll find first-magniude Fomalhaut in Piscis Austrinus, the Southern Fish. Fomalhaut is the solitary bright star low in the south. Using the eastern side of the square as a pointer to the south brings you to Diphda in the large, faint constellation of Cetus, the Whale.

To the east of the Square lies the Pleiades star cluster (M45) in Taurus, which reminds us of the forthcoming winter. By late evening in October and early evening in December, Taurus and Orion have both cleared the horizon, and Gemini is rising in the northeast. In concert with the reappearance of winter constellations, the view to the northwest finds summertime's Cygnus and Lyra about to set. The autumn season is a great transition period, both on Earth and in the sky, and a fine time to experience the subtleties of these constellations.

AUTUMN

1 A.M. on September 1; 11 P.M. on October 1; 9 P.M. on November 1. Add 1 hour for daylight-saving time



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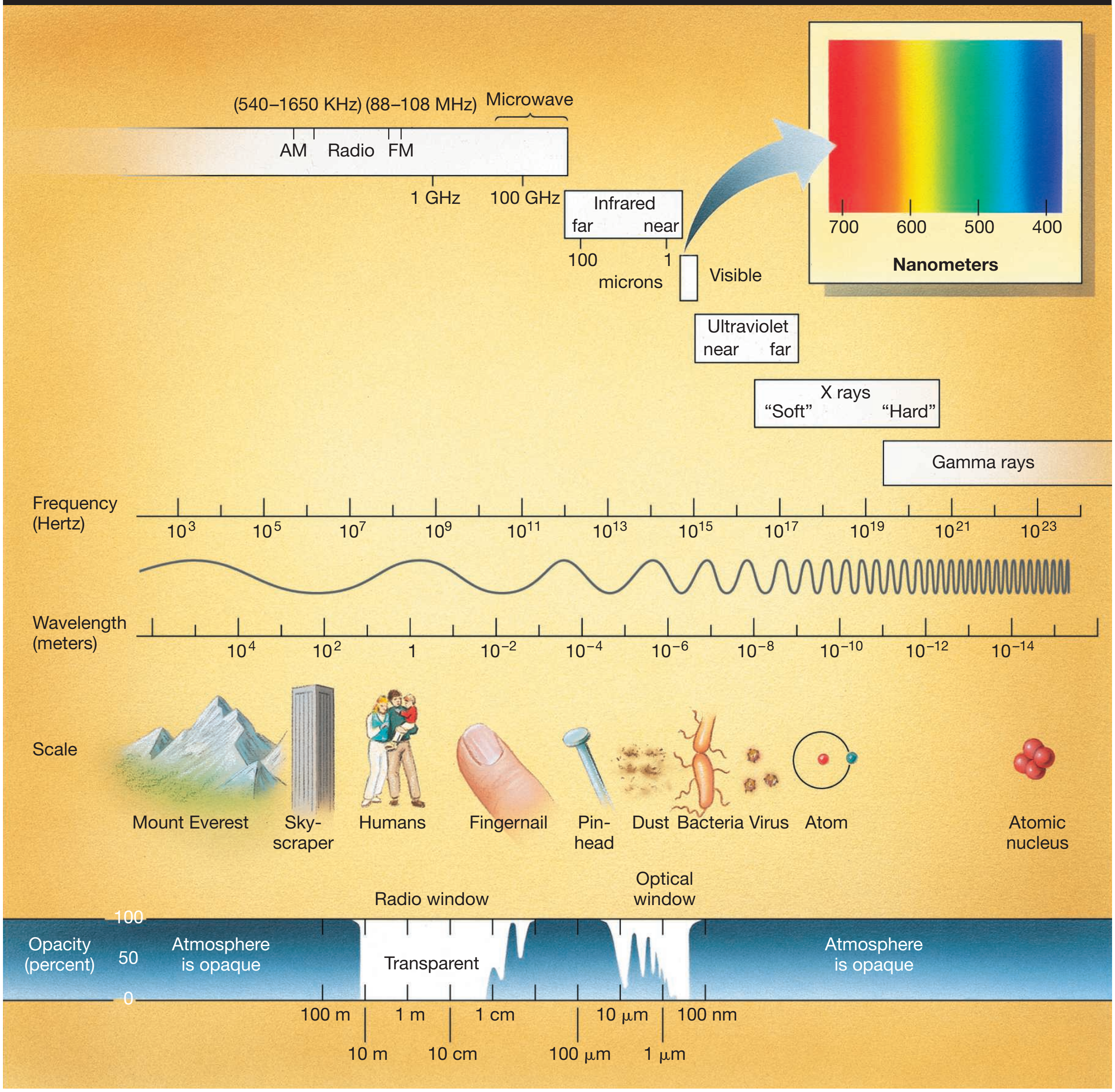
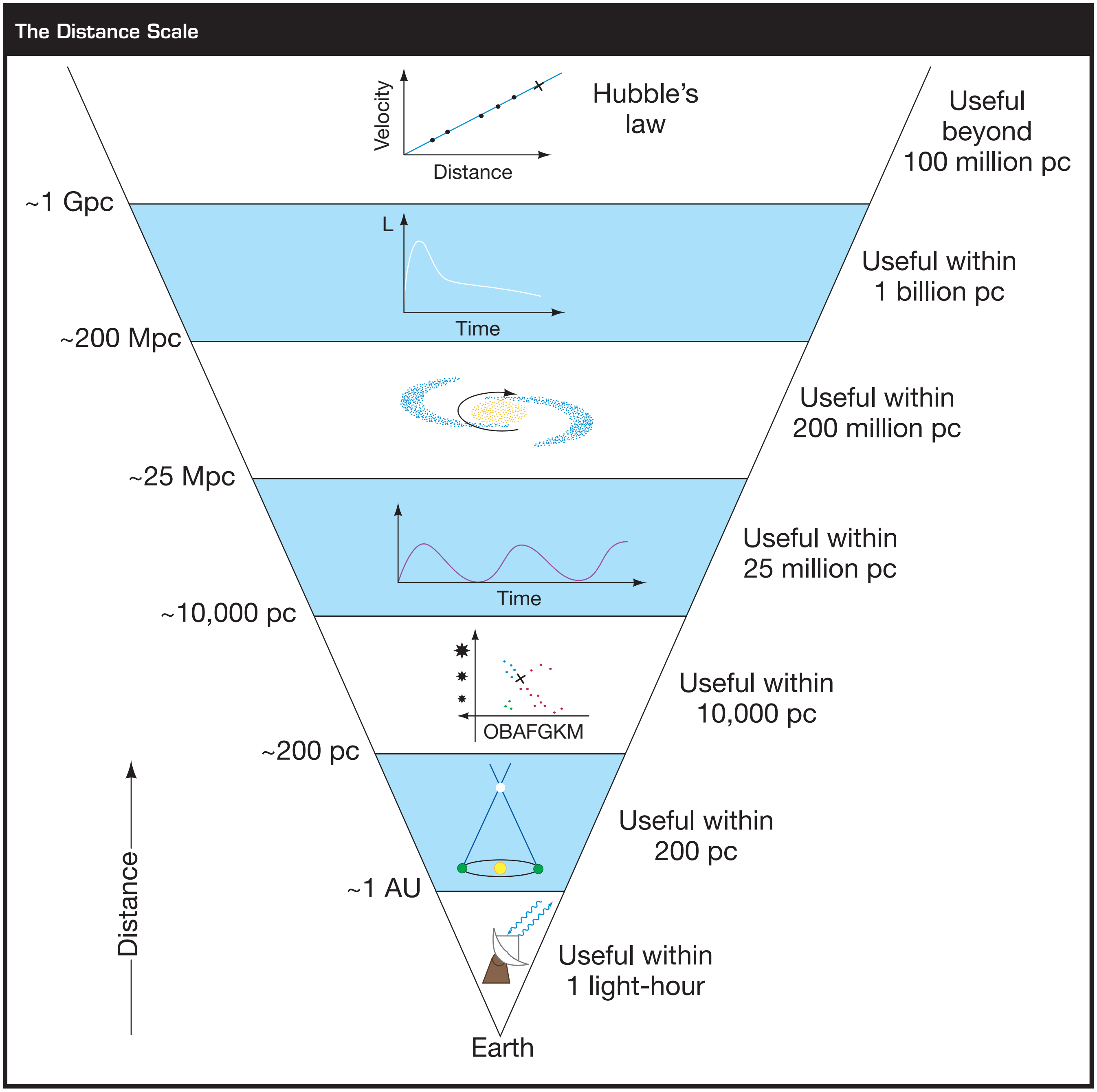
The Entire Electromagnetic Spectrum




The Distance Scale
Velocity
Distance
Hubble's law
Useful beyond 100 million pc
~1 Gpc
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Time
Useful within 1 billion pc
~200 Mpc
Useful within 200 million pc
~25 Mpc
Time
Useful within 25 million pc
~10,000 pc
OBAFGKM
Useful within 10,000 pc
~200 pc
Useful within 200 pc
~1 AU
Useful within 1 light-hour
Distance
Earth

EXPLORING the Galaxy and Beyond

▼ This spectacular image of the Sun was taken using multiple detectors aboard the *Solar Dynamics Observatory* spacecraft (*SDO*). In this composite, false-color view of the Sun's lower atmosphere, taken in the far ultraviolet part of the spectrum, red represents hot (2 million K) gas, green slightly cooler (1.3 million K) gas, and blue the coolest (600,000 K) material. Jets of superheated plasma can be seen erupting outward, the result of violent magnetic disturbances on the Sun's surface. Since its launch in early 2010, *SDO* has captured more than 100 million images of the Sun at visible and ultraviolet wavelengths, allowing researchers to study in unprecedented detail the ever-changing face of our parent star. (*Image credit*: *NASA/SDO*)

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In *Astronomy: A Beginner's Guide to the Universe*, trusted authors Eric Chaisson and Steve McMillan introduce the world of our galaxy and beyond. In a length ideal for one semester, the text focuses on three central themes to engage and excite students: the process of science, the size and scale of the universe, and the constant evolution of the cosmos. **The Eighth Edition** is up to date with the most recent discoveries in astronomy and is written to be visually engaging and dynamic for student audiences. An integral goal of the text is to focus on how we know what we know by clearly and concisely presenting scientific terms to the non-science student. An emphasis on critical thinking and visualization helps students to comprehend better and retain information longer.

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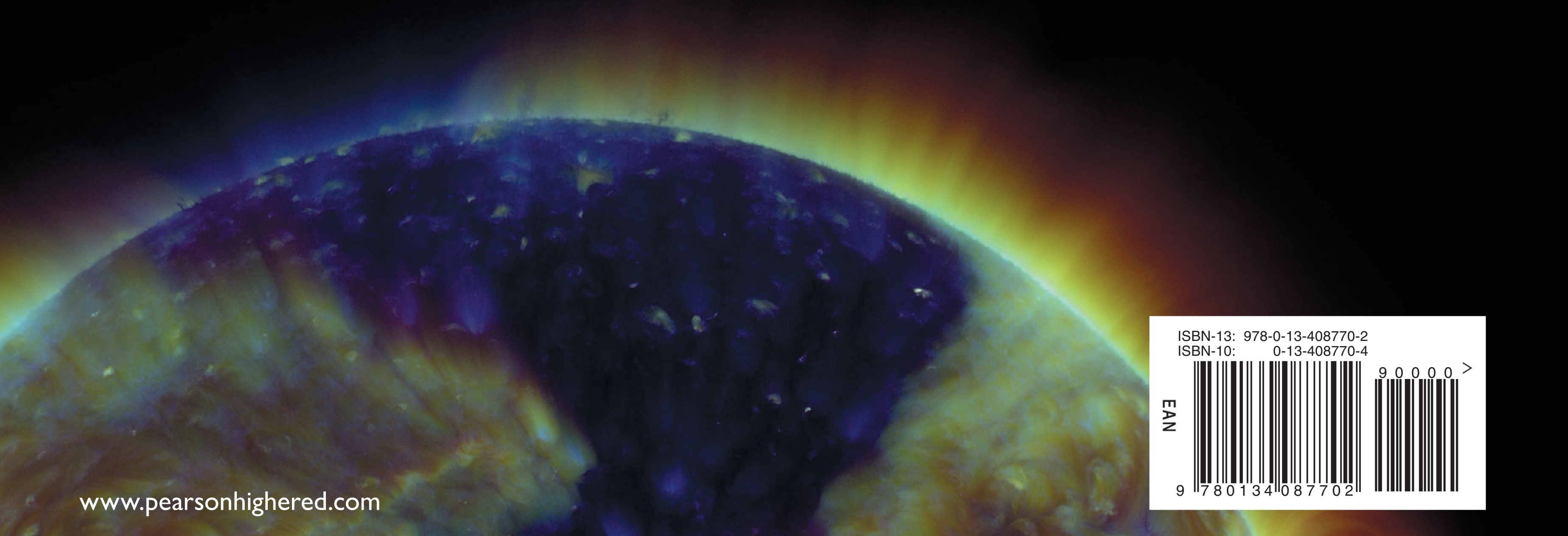

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