Figure 14.16 MA interactive photo

Spiral arms in Galaxy M51. This photo from the Hubble Space Telescope shows M51's two magnificent spiral arms along with a smaller galaxy that is currently interacting with one of those arms. Notice that the spiral arms are much bluer in color than the central bulge. Because massive blue stars live only for a few million years, the relative blueness of the spiral arms tells us that stars must be forming more actively within them than elsewhere in the galaxy. (The large image shows a region roughly 90,000 light-years across.)

surrounded by large, red ionization nebulae, trace out the arms, while the stars between the arms are generally redder and older. We also see enhanced amounts of molecular and atomic gas in the spiral arms, and streaks of interstellar dust often obscure the inner sides of the arms themselves. These features show that spiral arms contain both young stars and the material necessary to make new stars.

At first glance, spiral arms look as if they ought to move with the stars, like the fins of a giant pinwheel in space. However, we know that spiral arms cannot be fixed patterns of stars that rotate along with the galaxy, because stars near the center of the galaxy complete an orbit in much less time than stars far from the center. If the spiral arms simply moved along with the stars, the central parts of the arms would complete several orbits around the galaxy as the outer parts orbited just once. This difference in orbital periods would eventually wind up the spiral arms into a tight coil. We generally don't see such tightly wound spiral arms in galaxies, so we conclude that spiral arms are more like swirling ripples in a whirlpool than like the fins of a giant pinwheel.

Spiral arms are waves of star formation that spread through our galaxy's disk.

In fact, the evidence indicates that spiral arms are enormous waves of star formation that propagate through the gaseous disk of a spiral galaxy like the Milky Way. Theoretical models suggest that disturbances called **spiral density waves** produce the spiral arms. According to these models, spiral arms are places in a galaxy's disk where stars and gas clouds get more densely packed. Pushing the stars closer together has little effect on the stars themselves—they are still much too widely separated to collide with each other. However, the large gas clouds do collide, and packing the clouds closer together enhances the force of gravity within them, triggering the formation of new star clusters (Figure 14.17). Supernova explosions from massive stars in these clusters can then compress the surrounding clouds further, triggering even more star formation. As this long-lasting pattern of star formation propagates through the gas and stars of the galaxy's disk, it gradually becomes stretched into a spiral by the disk's rotation.

common Misconceptions

What Is a Nebula?

The term *nebula* means "cloud," but in astronomy it can refer to many different kinds of objects, which sometimes leads to misconceptions. Many astronomical objects look "cloudy" through small telescopes, and in past centuries astronomers called any such object a nebula as long as they were sure it wasn't a comet. For example, galaxies were called nebulae because they looked like fuzzy round or spiral blobs.

Using the term *nebula* to refer to a galaxy now sounds somewhat dated, given the enormous differences between these distant star systems and the much smaller clouds of gas that populate the interstellar medium. Nevertheless, some people still refer to spiral galaxies as "spiral nebulae." Today, we generally use the term *nebula* to refer only to interstellar clouds, but be aware that the term is still sometimes used in other ways.

Figure 14.17 MA interactive figure

Schematic illustration of star formation produced by spiral density waves. Stars and gas clouds pass through spiral arms as they orbit the galaxy. Each arm is a self-sustaining pattern because gravity slows down stars and gas clouds as they pass through an arm, causing them to be more densely packed there.

14.3 The History of the Milky Way

Now that we have discussed the basic properties of the Milky Way, we are ready to turn our attention to the history of our galaxy. All the galaxy's properties provide clues to its history. However, some of the most important clues come from a detailed comparison of disk stars with halo stars. We'll begin with this comparison, and then discuss a basic model of galaxy formation that explains many of the differences between these two groups of stars.

• What do halo stars tell us about our galaxy's history?

We have already seen how the disorderly orbits of halo stars differ from the generally circular orbits of disk stars. Two other differences between halo stars and disk stars give us clues to their origins. First, we don't find any young stars in the halo, while in the disk we see stars of many different ages. Second, the spectra of halo stars show that they contain fewer heavy elements than disk stars. Because of these differences, astronomers divide the Milky Way's stars into two distinct populations:

1. The **disk population** (sometimes called *Population I*) contains both young stars and old stars, all of which have heavy-element proportions of about 2%, like our Sun.
2. The **spheroidal population** (or *Population II*) consists of stars in the halo and the bulge, both of which are roughly spherical in shape. Stars in this population are always old and therefore low in mass, and those in the halo can have heavy-element proportions as low as 0.02%—meaning that heavy elements are about 100 times rarer in these stars than in the disk population.

Figure 14.18 MA interactive figure

This four-picture sequence illustrates a simple schematic model of galaxy formation, showing how a spiral galaxy might develop from a protogalactic cloud of hydrogen and helium gas.

We can understand why bulge and halo stars differ from disk stars by looking at how the Milky Way's gas is distributed. The halo does not contain the cold, dense molecular clouds required for star formation. In fact, the halo contains almost no gas at all, and that small amount of gas is generally quite hot. Because star-forming molecular clouds are found only in the disk, new stars can be born only in the disk and not in the halo.

Halo stars are all old with a very low proportion of heavy elements, while disk stars come in all ages and contain a higher proportion of heavy elements.

The relative lack of heavy elements in halo stars indicates that they must have formed early in the galaxy's history—before many supernovae had exploded and added heavy elements to star-forming clouds. We therefore conclude that the halo has lacked the gas needed for star formation for a very long time. Apparently, all the Milky Way's cool gas settled into the disk long ago. The only stars that still survive in the halo are long-lived, low-mass stars.

think about it How does the halo of our galaxy resemble the distant future fate of the galactic disk? Explain.

• How did our galaxy form?

Any model of our galaxy's formation must account for the differences between disk stars and halo stars. One of the earliest and most basic models proposed that our galaxy began as a giant **protogalactic cloud** containing all the hydrogen and helium gas that eventually turned into stars. Gravity would have caused such a cloud to contract and fragment, just as in present-day star-forming clouds **[Section 12.1]**.

According to this basic model, the stars of the spheroidal population (bulge and halo) formed first. Early on, gravity attracted matter from all directions into a cloud that was blobby in shape and had little or no measurable rotation. The orbits of stars forming within such a cloud could have had any orientation, accounting for the randomly oriented orbits of stars in the spheroidal population.

Later, the remaining gas contracted under the force of gravity and settled into a flattened, spinning disk because of conservation of angular momentum (Figure 14.18). This process was much like the process that leads to the formation of spinning disks of gas around young stars **[Sections 6.3, 12.1]**, but on a much larger scale. Collisions among gas particles tended to average out their random motions, leading them to acquire orbits in the same direction and in the same plane. Stars that formed within this spinning disk make up the disk population of stars.

Halo stars formed when our galaxy's protogalactic cloud was still large and blobby, and disk stars formed after the gas had settled into a spinning disk.

Detailed studies of the Milky Way's stars, as well as observations of other galaxies that we'll discuss in Chapter 15, support certain aspects of this basic model of galaxy formation but have shown that it is a bit too simplistic. All available evidence confirms that the stars in the Milky Way's halo are indeed very old. The main-sequence turnoff points in H-R diagrams of globular clusters show that their stars were born at least 12 billion years ago **[Section 11.3]**. Individual halo stars and some of the bulge stars are similarly old. Furthermore, the proportions of heavy elements in halo stars are quite low, demonstrating that they formed before many generations of supernovae had a chance to enrich the Milky Way's interstellar medium.

However, careful studies of the heavy element proportions in halo stars suggest that our galaxy formed from multiple clouds. If the Milky Way had formed from a single protogalactic cloud, it would have steadily accumulated heavy elements during its inward collapse as stars formed and exploded within it. In that case, the outermost stars in the halo would be the oldest and would have the smallest proportions of heavy elements, and the heavy element proportions would steadily rise as we looked at stars orbiting closer to the disk. But that is not the pattern we observe.

Our galaxy's halo stars may have formed in several small protogalactic clouds that later merged to form one large protogalactic cloud.

Instead, we find variations in heavy element proportions, suggesting that the Milky Way's oldest stars formed in relatively small protogalactic clouds, each with a few globular clusters. These clouds later collided and combined to create the full protogalactic cloud that became the Milky Way (Figure 14.19). Similar processes may still be under way. Recall that the Sagittarius and Canis Major dwarf galaxies are currently being torn apart as they crash through the Milky Way's disk. A billion years from now, their stars will be indistinguishable from halo stars, because they will all be circling the Milky Way on orbits that carry them high above the disk. Evidence indicates that this process has also occurred in the past: Some halo stars move in organized streams that are probably the remnants of dwarf galaxies torn apart long ago by the Milky Way's gravity.

Figure 14.19

This painting shows a model of how the Milky Way's halo may have formed. The characteristics of stars in the Milky Way's halo suggest that several smaller gas clouds, already bearing some stars and globular clusters, may have merged to form the Milky Way's protogalactic cloud. These stars and star clusters remained in the halo while the gas settled into the Milky Way's disk.

think about it If the preceding scenario is true, then the Milky Way suffered several collisions early in its history. Explain why we think that galaxy collisions (or collisions between protogalactic clouds) were common in the distant past. (*Hint:* How did the average separations of galaxies in the past compare to their average separations today?)

The distribution of elements in the Milky Way's disk and bulge suggests that when the disk finally formed, it began with only about 10% as many heavy elements as it has today, but with a greater concentration of heavy elements toward the center. Observations of old stars in the bulge of our galaxy show that the gas clouds from which some of the bulge stars formed had a chemical composition similar to that of our Sun, even though they gave birth to those stars more than 10 billion years ago.

Evidence indicates that after the Milky Way's disk was in place, the star–gas–star cycle gradually increased the disk's heavy element content in a more orderly fashion. Because this cycle has operated continuously since the disk formed, the ages of disk stars range from newly born to 10 billion or more years old. We expect star formation to continue in the disk as long as enough gas remains within it.

MA Black Holes Tutorial, Lessons 1–2

14.4 The Mysterious Galactic Center

The center of the Milky Way Galaxy lies in the direction of the constellation Sagittarius. This region of the sky does not look particularly special to our unaided eyes. However, if we could remove the interstellar dust that obscures our view, the galaxy's central bulge would be one of the night sky's most spectacular sights. And deep within the bulge may lurk a gigantic black hole with a mass as great as 4 million times the mass of our Sun.

a This infrared image shows stars and gas clouds within 1000 light-years of the center of the Milky Way.

b This radio image shows vast threads of emission tracing magnetic field lines near the galactic center.

c This radio image zooms in on gas swirling around the radio source Sgr A* (marked by the white dot), suspected to contain a very massive black hole.

d This infrared image shows stars within about 1 light-year of Sgr A*. The two arrows point to the precise location of Sgr A*.

Figure 14.20 MA interactive photo

Zooming into the galactic center at infrared and radio wavelengths.

• What lies in the center of our galaxy?

Although the Milky Way's clouds of gas and dust prevent us from seeing visible light from the center of the galaxy, we can peer into the heart of our galaxy with radio, infrared, and X-ray telescopes. Figure 14.20 shows a series of infrared and radio views, looking ever deeper into the galaxy's center. Within about 1000 light-years of the center, we find swirling clouds of gas and a cluster of several million stars. Bright radio emission traces out the magnetic fields that thread this turbulent region. In the exact center we find a source of radio emission named Sagittarius A* (pronounced "Sagittarius A-star"), or Sgr A* for short, that is quite unlike any other radio source in our galaxy.

see it for yourself Use the star charts in Appendix I to find the constellation Sagittarius, which is easily visible on summer and fall evenings and looks like a teapot with a handle on the left and a spout on the right. The center of the Milky Way Galaxy is near the tip of the spout. Can you see the Milky Way's faint band of light passing through the constellations Sagittarius, Cygnus, and Casseopeia?

Figure 14.21

This diagram shows stellar positions (colored dots) observed with the Keck telescope and calculated orbits (dashed lines) for several stars near the center of the galaxy. By applying Newton's version of Kepler's third law, we infer that the central object has a mass about 4 million times that of our Sun, packed into a space so small that the object is almost certainly a black hole.

Several hundred stars crowd the region within a light-year of Sgr A*, and their motions indicate the presence of an extremely massive object. Figure 14.21 shows the orbital paths of some of these stars as measured over the past decade. Notice that some of them swoop within just a few light-hours of the central object. Applying Newton's version of Kepler's third law to the orbits of these stars shows that the central object has a mass of about 4 million solar masses, all packed into a region of space just a little larger than our solar system. An object that massive within such a small space is almost certainly a black hole.

Stars quite close to our galaxy's center orbit a nearly invisible and tiny object about 4 million times as massive as our Sun—probably a huge black hole.

However, some aspects of Sgr A* remain puzzling. Most suspected black holes are thought to accumulate matter through accretion disks that radiate brightly in X rays. These include black holes in binary star systems like Cygnus X-1 **[Section 13.3]** and some giant black holes at the centers of other galaxies **[Section 15.4]**. If the black hole at the center of our galaxy had an accretion disk, its

X-ray light would easily penetrate the dusty gas of our galaxy and appear fairly bright to our X-ray telescopes. Yet at most times, the X-ray emission from Sgr A* is relatively faint.

Observations of Sgr A* made in other wavelengths of light are helping us understand this surprising behavior. For example, enormous X-ray flares have been observed coming from the location of the suspected black hole (Figure 14.22). These sudden changes in X-ray brightness probably come from energy released by comet-sized lumps of matter torn apart by the black hole's tidal forces just before disappearing beneath its event horizon. If we continue to observe similar X-ray flares from Sgr A*, then the explanation for its generally low X-ray brightness may be that matter falls into it in big chunks instead of from a smooth, swirling accretion disk. Until we better understand Sgr A*, it is sure to remain a favorite target for observation.

Figure 14.22

This X-ray image shows the central 60 light-years of our galaxy. The circled white dot is an X-ray flare from the suspected black hole at the Milky Way's center. The flare probably came from energy released by a comet-size lump of matter that was torn apart by tidal forces just before it disappeared into the black hole.

the big picture

Putting Chapter 14 into Perspective

In this chapter, we have explored the structure, motion, and history of our galaxy, along with the galactic recycling that has made our existence possible. As you review, keep in mind these "big picture" ideas:

- The inability of visible light to pass through interstellar gas and dust concealed the true nature of our galaxy until recent times. Modern astronomical instruments reveal the Milky Way Galaxy to be a dynamic system of stars and gas that continually gives birth to new stars and planetary systems.
- Stellar winds and explosions make interstellar space a violent place. Hot gas tears through the atomic hydrogen that fills much of the galactic disk, leaving expanding bubbles and fast-moving clouds in its wake. All this violence might seem dangerous, but it performs the great service of mixing new heavy elements into the gas of the Milky Way.
- Although the elements from which we are made were forged in stars, we could not exist if stars were not organized into galaxies. The Milky Way Galaxy acts as a giant recycling plant, converting gas expelled from each generation of stars into the next generation and allowing some heavy elements to solidify into planets like our own.

summary of key concepts

14.1 The Milky Way Revealed

• What does our galaxy look like?

The Milky Way Galaxy consists of a thin **disk** about 100,000 light-years in diameter with a central bulge and a spherical region called the **halo** that surrounds the entire disk. The disk contains most of the gas and dust of the **interstellar medium**, while the halo contains only a small amount of hot gas and virtually no cold gas.

• How do stars orbit in our galaxy?

Stars in the disk all orbit the galactic center in about the same plane and in the same direction. Halo and bulge stars also orbit the center of the galaxy, but their orbits are randomly inclined to the disk of the galaxy. Orbital motions of stars allow us to determine the distribution of mass in our galaxy.

14.2 Galactic Recycling

• How is gas recycled in our galaxy?

Stars are born from the gravitational collapse of gas clumps in **molecular clouds**. Massive stars explode as supernovae when they die, creating hot **bubbles** in the interstellar medium that contain the new elements made by these stars. Eventually, this gas cools and mixes with the interstellar medium, turning into atomic hydrogen gas and then cooling further, producing star-forming molecular clouds. We call this process the **star–gas–star cycle**.

• Where do stars tend to form in our galaxy?

Active star-forming regions, marked by the presence of hot, massive stars and ionization nebulae, are found mostly in **spiral arms**. In each arm, a **spiral density wave** causes gas clouds to crash into each other and to form clusters of new stars.

14.3 The History of the Milky Way

• What do halo stars tell us about our galaxy's history?

The halo generally contains only old, low-mass stars that have a much smaller proportion of heavy elements than stars in the disk. Halo stars therefore must have formed early in the galaxy's history, before the gas settled into a disk.

• How did our galaxy form?

Halo stars probably formed in several different **protogalactic clouds** of hydrogen and helium gas. Gravity pulled those clouds together to form a single larger one. The collapse of this cloud continued until it formed a spinning disk around the galactic center. Stars have formed continuously in the disk since that time, but stars no longer form in the halo.

14.4 The Mysterious Galactic Center

• What lies in the center of our galaxy?

Motions of stars near the center of our galaxy suggest that it contains a black hole about 4 million times as massive as the Sun. The black hole appears to be powering a bright source of radio emission known as Sgr A*.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 14 Visual Quiz at www.masteringastronomy.com.

Visible light from stars

Infrared light from stars

Radio emission from molecules

X-ray emission from hot gas

The images above, taken from Figure 14.11, show what the central region of our galaxy looks like from our viewpoint in different wavelengths of light. Each image shows the same region of the sky. Use the following questions to check your understanding of what these images show and what we can learn by comparing them.

1. The image of radio emission uses different colors of light to represent different levels of brightness. Which color represents the brightest radio emission? Which color represents the lowest levels of brightness?
2. The image of X-ray emission uses different colors of light to represent different levels of brightness. The dark blue color represents the lowest levels of X-ray brightness. Which color represents the greatest levels of X-ray brightness?
3. How do regions showing strong radio emission from molecules look in the visible-light image? Are they bright or are they dark?
4. How do regions showing strong radio emission from molecules look in the infrared-light image? Are they bright or are they dark?
5. Compare the radio, infrared, and visible-light images. Which of the following conclusions is best supported by your comparison?
   a. Gas clouds containing molecules absorb roughly equal amounts of infrared starlight and visible starlight.
   b. Gas clouds containing molecules absorb substantial amounts of visible starlight but don't absorb infrared starlight at all.
   c. Gas clouds containing molecules absorb infrared starlight less effectively than they absorb visible starlight.
6. Compare the radio and X-ray images. Can you conclude from this comparison that gas clouds containing molecules absorb X-ray light?

exercises and problems

Mastering ASTRONOMY®

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Review Questions

1. Draw simple sketches of our galaxy as it would appear face-on and edge-on. Identify the *disk, bulge, halo,* and *spiral arms,* and indicate the galaxy's approximate dimensions.
2. What are the Large and Small Magellanic Clouds, and the Sagittarius and Canis Major Dwarfs?
3. Describe the basic characteristics of stellar orbits in the bulge, disk, and halo of our galaxy.
4. How can we use orbital properties to learn about the mass of the galaxy? What have we learned?
5. Summarize the stages of the star–gas–star cycle in Figure 14.3.
6. What creates a bubble of hot, ionized gas? What happens to the gas in the bubble over time?
7. What are *cosmic rays,* and where are they thought to come from?
8. What do we mean by *atomic hydrogen gas?* How common is it, and how do we map its distribution in the galaxy?
9. Briefly summarize the different types of gas present in the disk of the galaxy, and describe how they appear when we view the galaxy in different wavelengths of light.
10. What are *ionization nebulae*, and why are they found near hot, massive stars?
11. How do we know that spiral arms do not rotate like giant pinwheels? What makes spiral arms bright?
12. What triggers star formation within a spiral arm? How do we think spiral arms are maintained?
13. Briefly describe the characteristics that distinguish the galaxy's *disk population* of stars from its *spheroidal population* of stars.
14. Why do we think that the Milky Way formed from the merger of several smaller protogalactic clouds?
15. What is Sgr A*? What evidence suggests that it contains a massive black hole?

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

16. We did not understand the true size and shape of our galaxy until NASA launched satellites into the galactic halo, enabling us to see what the Milky Way looks like from the outside.
17. Planets like Earth probably didn't form around the first stars because there were so few heavy elements back then.
18. If I could see infrared light, the galactic center would look much more impressive.
19. Many spectacular ionization nebulae are seen throughout the Milky Way's halo.
20. The carbon in my diamond ring was once part of an interstellar dust grain.
21. The Sun's velocity around the Milky Way tells us that most of our galaxy's dark matter lies near the center of the galactic disk.
22. We know that a black hole lies at our galaxy's center because numerous stars near it have vanished over the past several years, telling us that they've been sucked in.
23. If we could watch a time-lapse movie of a spiral galaxy over millions of years, we'd see many stars being born and dying within the spiral arms.
24. The star–gas–star cycle will keep the Milky Way looking just as bright in 100 billion years as it looks now.
25. Halo stars orbit the center of our galaxy much faster than the disk stars.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

26. What is the shape of the Milky Way's halo? (a) round like a ball (b) flat like a disk (c) flat like a disk but with a hole in the center
27. Where are most of the Milky Way's globular clusters found? (a) in the disk (b) in the bulge (c) in the halo
28. Why do disk stars bob up and down as they orbit the galaxy? (a) because the gravity of other disk stars always pulls them toward the disk (b) because of friction with the interstellar medium (c) because the halo stars keep knocking them back into the disk
29. How do we determine the Milky Way's mass outside the Sun's orbit? (a) from the Sun's orbital velocity and its distance from the center of our galaxy (b) from the orbits of halo stars near the Sun (c) from the orbits of stars and gas clouds orbiting the galactic center at greater distances than the Sun
30. Where in our galaxy would you find the coldest gas in the interstellar medium? (a) the disk (b) the halo (c) the bulge

31. What is the typical percentage of elements other than hydrogen and helium in stars that are forming right now in the vicinity of the Sun? (a) 20% (b) 2% (c) 0.02%
32. Which of these forms of radiation passes most easily through the disk of the Milky Way? (a) red light (b) blue light (c) infrared light
33. Where would be the most likely place to find an ionization nebula? (a) in the halo (b) in the bulge (c) in a spiral arm
34. Which kind of star is most likely to be part of the spheroidal population? (a) an O star (b) an A star (c) an M star
35. We measure the mass of the black hole at the galactic center from (a) the orbits of stars in the galactic center. (b) the orbits of gas clouds in the galactic center. (c) the amount of radiation coming from the galactic center.

Process of Science

36. *Discovering the Structure of the Milky Way.* The story of how we came to learn the structure of the Milky Way (see Special Topic, p. 388) is an excellent demonstration of how science progresses. What features of the Milky Way's appearance in our sky led scientists to conclude that its width is much larger than its thickness? Why did they originally believe that the Sun was near the Milky Way's center? What key observations forced scientists to change their views about the location of the Sun within the Milky Way?
37. *Formation of the Milky Way.* Figure 14.18 outlines a basic model for the formation of the Milky Way Galaxy that accounts for some of our galaxy's observed features but not all of them. What observational evidence suggests that the Milky Way's protogalactic cloud contained only hydrogen and helium? What evidence suggests that the halo stars formed first? Why do we think that the disk stars formed after the protogalactic cloud collapsed into a spinning disk? What is the evidence that stars have been forming steadily in the disk for billions of years? What features of the Milky Way are not explained by this basic model?

Group Work Exercise

38. *Star Clusters and Milky Way Structure.* Star clusters are not evenly distributed in the sky, and their locations provide clues about the history of our galaxy. In this exercise you will determine where different kinds of star clusters are located in relation to the disk of the Milky Way, using the all-sky diagram in Appendix H, and discuss the significance of the patterns you find. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes).
    a. The *Scribe* and *Proposer* should work together to investigate the locations of globular clusters relative to the Milky Way's disk and relative to the galactic center, which is in the constellation Sagittarius. Globular clusters can be found in the following constellations: Aquarius, Aquila, Canes Venatici, Capricornus, Carina, Centaurus, Columba, Coma Berenices, Hercules, Hydra, Lepus, Lynx, Lyra, Musca, Ophiuchus, Pegasus, Puppis, Sagittarius, Scorpius, Sculptor, Serpens, Tucana, and Vela.
    b. The *Moderator* and *Skeptic* should work together to investigate the locations of young open clusters relative to the Milky Way's disk and relative to the galactic center. Open clusters with ages of 100 million years or less can be found in the following constellations: Canis Major, Carina, Cassiopeia, Crux, Cygnus, Monoceros, Norma, Ophiuchus, Perseus, Puppis, Sagittarius, Scorpius, Scutum, Serpens, Taurus, and Vela.
    c. As a team, compare the locations of the two sets of clusters and describe the differences you find.
    d. The *Proposer* should offer an explanation for these differences.
    e. The *Skeptic* should propose an alternative explanation.
    f. The *Moderator* and *Scribe* should discuss these explanations and list some observations that astronomers could perform to determine which explanation is better.

Investigate Further

Short-Answer/Essay Questions

39. *Unenriched Stars.* Suppose you discovered a star made purely of hydrogen and helium. How old do you think it would be? Explain.
40. *Enrichment of Star Clusters.* The gravitational pull of an isolated globular cluster is rather weak—a single supernova explosion can blow all the interstellar gas out of a globular cluster. How might this fact relate to observations indicating that stars ceased to form in globular clusters long ago? How might it relate to the fact that globular clusters are deficient in elements heavier than hydrogen and helium? Summarize your answers in one or two paragraphs.
41. *High-Velocity Star.* The average speed of stars in the solar neighborhood relative to the Sun (i.e., the speed at which we see stars moving toward or away from the Sun—*not* their orbital speed around the galaxy) is about 20 km/s. Suppose you discover a star in the solar neighborhood that is moving at a much higher speed relative to the Sun—say, 200 km/s. What kind of orbit does this star probably have around the Milky Way? In what part of the galaxy does it spend most of its time? Explain.
42. *Research: Discovering the Milky Way.* Humans have been looking at the Milky Way since long before recorded history, but only in the past century did we verify the true shape of the galaxy and our location within it. Learn more about how conceptions of the Milky Way developed through history. What names did different cultures give the band of light they saw? What stories did they tell about it? How have ideas about the galaxy changed in the past few centuries? Try to locate diagrams that illustrate these changes. Write a two- to three-page summary of your findings.
43. *Future of the Milky Way.* Describe how the Milky Way would look from the outside if you could watch it for the next 100 billion years. How would its appearance change?
44. *Orbits at the Galactic Center.* Using the information in Figure 14.21, identify which two stars reach the highest orbital speeds. Explain how the orbits of those two stars illustrate Kepler's first two laws.
45. *A Nonspinning Galaxy.* How would the development of the Milky Way Galaxy have been different if its original protogalactic cloud had no angular momentum? Describe how you think our galaxy would look today and explain your reasoning.
46. *Gas Distribution in the Milky Way.* Make a sketch of the gas distribution in the plane of the Milky Way, based on the photographs in Figure 14.11. In your sketch, map out where you would find molecular clouds, atomic hydrogen clouds, and bubbles of hot gas. Explain why each of those components of the interstellar medium is found in the location where you have drawn it.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

47. *Mass of the Milky Way's Halo.* The Large Magellanic Cloud is a small galaxy that orbits the Milky Way. It is currently orbiting the Milky Way at a distance of roughly 160,000 light-years from the galactic center at a velocity of about 300 km/s. Use these values in the orbital velocity law to get an estimate of the Milky Way's mass within 160,000 light-years from the center.
48. *Mass of the Central Black Hole.* Suppose you observed a star orbiting the galactic center at a speed of 1000 km/s in a circular orbit with a radius of 20 light-days. What would your estimate be for the mass of the object that the star was orbiting?
49. *Mass of a Globular Cluster.* Stars in a typical globular cluster orbit the center at speeds of about 10 km/s. Stars at the outskirts of a globular cluster are about 50 light-years from the center. Use these facts to estimate the mass of a typical globular cluster.
50. *Mass of Saturn.* The innermost rings of Saturn orbit in a circle with a radius of 67,000 kilometers at a speed of 23.8 km/s. Use the orbital velocity law to compute the mass contained within the orbit of those rings. Compare your answer with the mass of Saturn listed in Appendix E.

Discussion Questions

51. *Galactic Ecosystem.* We have likened the star–gas–star cycle in our Milky Way to the ecosystem that sustains life on Earth. Here on our planet, water molecules cycle from the sea to the sky to the ground and back to the sea. Our bodies convert atmospheric oxygen molecules into carbon dioxide, and plants convert carbon dioxide back into oxygen molecules. How are the cycles of matter on Earth similar to the cycles of matter in the galaxy? How do they differ? Do you think the term *ecosystem* is appropriate in discussions of the galaxy?
52. *Galaxy Stuff.* In the chapters on stars, we learned why we are "star stuff." Explain why we are also "galaxy stuff." Does the fact that the entire galaxy was involved in bringing forth life on Earth change your perspective on Earth or on life? If so, how? If not, why not?

Web Projects

53. *Images of the Star–Gas–Star Cycle.* Find pictures on the Web of ionization nebulae and other forms of interstellar gas in different stages of the star–gas–star cycle. Assemble the pictures into a sequence that tells the story of interstellar recycling, with a one-paragraph explanation of each image.
54. *The Galactic Center.* Search the Web for recent images of the galactic center, along with information on the question of whether the center hides a massive black hole. Write a two- to three-page report, with pictures, on the latest findings about the center of the Milky Way Galaxy.

15

Galaxies and the Foundation of Modern Cosmology

learning goals

15.1 Islands of Stars

- What are the three major types of galaxies?
- How are galaxies grouped together?

15.2 Distances of Galaxies

- How do we measure the distances to galaxies?
- What is Hubble's law?
- How do distance measurements tell us the age of the universe?

15.3 Galaxy Evolution

- How do we observe the life histories of galaxies?
- How did galaxies form?
- Why do galaxies differ?

15.4 Quasars and Other Active Galactic Nuclei

- What are quasars?
- What is the power source for quasars and other active galactic nuclei?
- Do supermassive black holes really exist?

Far beyond the Milky Way, we see billions of other galaxies scattered throughout space. Some look similar to our own galaxy, while others look quite different. The sight of all these galaxies inspires us not only to wonder how they came to be, but also to ask fundamental questions about our universe: How old is the universe? How big is it? How is the universe changing with time? Such questions might have seemed ridiculously speculative a century ago. Today, we believe we know the answers to these questions with respectable accuracy.

Edwin Hubble, the man for whom the Hubble Space Telescope is named, provided the key discovery when he proved conclusively that galaxies exist beyond the Milky Way. The distances he measured to those galaxies revealed an astonishing fact: The more distant a galaxy is, the faster it moves away from us. Hubble's discovery dealt a mortal blow to the traditional belief in a static, eternal, and unchanging universe. The motions of the galaxies away from one another imply that the entire universe is expanding and that its age is finite.

In this chapter, we will get acquainted with the islands of stars we call galaxies. We will discuss how we measure their distances and how learning their distances has helped us determine the age and size of our universe. Finally, we will study galaxies themselves, looking for clues to how they have evolved through time and what they can tell us about the history of our universe as a whole.

essential preparation

1. How do galaxies move within the universe? **[Section 1.3]**
2. How do we measure stellar luminosities? **[Section 11.1]**
3. Where do stars tend to form in our galaxy? **[Section 14.2]**
4. How did our galaxy form? **[Section 14.3]**
5. What lies in the center of our galaxy? **[Section 14.4]**

15.1 Islands of Stars

Figure 15.1 shows an amazing image of a tiny patch of the sky taken by the Hubble Space Telescope. The telescope pointed in a single direction in the sky and collected all the light it could for 10 days. If you held a grain of sand at arm's length, the angular size of the grain would match the angular size of everything in this picture. Almost every blob of light in this image is a galaxy—an island of stars bound together by gravity. Like our own Milky Way, each galaxy is a dynamic system that has cycled hydrogen gas through stars for billions of years, producing new elements for future generations of stars. We can use this photo to estimate the total number of galaxies in the observable universe: We simply count the number of galaxies in this photo and multiply by the number of such photos it would take to make a montage of the entire sky. Careful counts from this photo and the even more detailed photo shown on page 1 tell us that the observable universe contains well over 100 billion galaxies.

Even without knowing the distances to the individual galaxies in Figure 15.1, we can see that galaxies come in many sizes, colors, and shapes. Some look large, some small. Some are reddish, some whitish. Some appear round, and some appear flat. We would like to understand why galaxies differ in these ways, but it is not easy to learn their histories. Just as with stars, our observations capture only the briefest

Figure 15.1

The Hubble Deep Field (far right) is an image composed of 10 days of exposures taken with the Hubble Space Telescope. Some of the galaxies pictured are more than three-quarters of the way across the observable universe. The zoom-in sequence shows the location of the field within the Big Dipper, recognizable in the lower left frame.

instant in any galaxy's life, leaving us to piece together the life story of a typical galaxy from pictures of different galaxies at various life stages.

The task is made even more difficult because we see young galaxies only at great distances—distances at which we are looking far back into the universe's past (see Figure 1.4). This fact means that the study of galaxies is intimately connected with what we call **cosmology**—the study of the overall structure and evolution of the universe. We'll therefore need to study not only galaxies in this chapter, but also our modern understanding of how universal expansion affects the lives of galaxies. We begin with an attempt to categorize the galaxies we see nearby, whose details are easier to observe.

• What are the three major types of galaxies?

Astronomers classify galaxies into three major categories:

- **Spiral galaxies,** such as our own Milky Way, look like flat white disks with yellowish bulges at their centers. The disks are filled with cool gas and dust, interspersed with hotter ionized gas, and usually display beautiful spiral arms.
- **Elliptical galaxies** are redder, rounder, and often longer in one direction than in the other, like a football. Compared with spiral galaxies, elliptical galaxies contain very little cool gas and dust, though they often contain very hot ionized gas.
- **Irregular galaxies** appear neither disklike nor rounded.

The differing colors of galaxies arise from the different kinds of stars that populate them: Spiral and irregular galaxies look white because they contain stars of all different colors and ages, while elliptical galaxies look redder because old, reddish stars produce most of their light. Galaxies also come in a wide range of sizes, from *dwarf galaxies* containing as few as 100 million (10^8) stars to *giant galaxies* with more than 1 trillion (10^{12}) stars.

Galaxies come in three major types: spiral, elliptical, and irregular.

think about it Take a moment and try to classify the larger galaxies in Figure 15.1. How many appear spiral? Elliptical? Irregular? Do the colors of galaxies seem related to their shapes?

Spiral Galaxies Like the Milky Way, other spiral galaxies also have a thin *disk* extending outward from a central *bulge* (Figure 15.2). The bulge merges smoothly into a *halo* that can extend to a radius of more than 100,000 light-years. However, the halo is difficult to see in photographs because its stars are generally dim and spread over a large volume.

Spiral galaxies have a disk, bulge, and halo like the Milky Way.

Recall that the Milky Way is made up of two distinct populations of stars **[Section 14.3]**. The *disk population* (sometimes called Population I) includes stars of all ages and masses that orbit in the disk of the galaxy. The *spheroidal population* (sometimes called Population II) consists of halo and bulge stars, with the halo stars generally being old and low in mass. We find the same two populations in other spiral galaxies, and we use them to define two primary components of galaxies:

- The **disk component** is the flat disk in which stars follow orderly, nearly circular orbits around the galactic center. The disk component always contains an *interstellar medium* of gas and dust, but the amounts and proportions of molecular, atomic, and ionized gases in this medium differ from one spiral galaxy to the next.
- The bulge and halo together make up the **spheroidal component**, named for its rounded shape. Stars in the spheroidal component have orbits with many different inclinations, and the spheroidal component generally contains little cool gas and dust. Figure 15.3 shows a spiral galaxy with an unusually large bulge that illustrates the general shape of the spheroidal component.

All spiral galaxies have both a disk and a spheroidal component, but there are some variations on the general theme. Some spiral galaxies appear to have a straight bar of stars cutting across the center, with spiral arms curling away from the ends of the bar. Such galaxies are known as *barred spiral galaxies* (Figure 15.4). Astronomers suspect that the Milky Way itself is a barred spiral galaxy, because our galaxy's bulge appears to be somewhat elongated.

Other galaxies have disk and spheroidal components like spiral galaxies but appear to lack spiral arms. These *lenticular galaxies* (*lenticular* means "lens-shaped") are sometimes considered an intermediate class between spirals and ellipticals, because they tend to have less cool gas than normal spirals but more than ellipticals. Among large galaxies in the universe, most (75–85%) are spiral or lenticular. Galaxies with obvious disks are much rarer among small galaxies.

Figure 15.2 MA interactive photo

The giant spiral galaxy M101. It is about 170,000 light-years in diameter.

Figure 15.3

NGC 4594 (the Sombrero Galaxy) is a spiral galaxy with a large bulge and a dusty disk that we see almost edge-on. A much larger but nearly invisible halo surrounds the entire galaxy. The bulge and halo together make up the spheroidal component of the galaxy. The region shown in this image is about 82,000 light-years across.

Figure 15.4

NGC 1300, a barred spiral galaxy about 110,000 light-years in diameter.

Elliptical Galaxies Elliptical galaxies differ from spiral galaxies primarily in that they have *only* a spheroidal component and lack a significant disk component. That is, elliptical galaxies look much like the bulge and halo of a spiral galaxy that is missing its disk. (For this reason, elliptical galaxies are sometimes called *spheroidal galaxies.*) Although the most massive galaxies are the relatively rare *giant elliptical galaxies* (Figure 15.5), the vast majority of elliptical galaxies are small. These small elliptical galaxies are the most common type of galaxy in the universe. Particularly small ellipticals with less than about a billion stars, known as *dwarf elliptical galaxies,* are often found near larger spiral galaxies. For example, over a dozen dwarf elliptical galaxies belong to our Local Group.

Elliptical galaxies differ from spiral galaxies in that they do not have significant disks.

Elliptical galaxies usually contain very little dust or cool gas, although some have relatively small and cold gaseous disks rotating at their centers. However, some large elliptical galaxies contain substantial amounts of very hot gas. This low-density, X-ray–emitting gas is much like the gas in the hot bubbles created by supernovae and powerful stellar winds in the Milky Way **[Section 14.2]**.

The lack of cool gas in elliptical galaxies means that, like the halo of the Milky Way, they generally have little or no ongoing star formation. Elliptical galaxies therefore look red or yellow in color because they do not have any of the hot, young, blue stars found in the disks of spiral galaxies.

Figure 15.5

M87, a giant elliptical galaxy in the Virgo Cluster, is one of the most massive galaxies in the universe. The region shown is more than 300,000 light-years across.

Irregular Galaxies Some of the galaxies we see nearby fall into neither of the two major categories. This class of *irregular galaxies* is a miscellaneous class, encompassing small galaxies such as the Magellanic Clouds (Figure 15.6) and larger "peculiar" galaxies that appear to be in disarray.

Irregular galaxies appear to be in disarray.

These blobby star systems are usually white and dusty, like the disks of spirals. Their colors tell us that they contain young, massive stars. Among nearby galaxies, only a small percentage of galaxies as large as the Milky Way are irregular. Telescopic observations probing deeper into the universe show that distant galaxies

are more likely to be irregular in shape than nearby galaxies. Because the light of more distant galaxies has taken longer to reach us, these observations tell us that irregular galaxies were more common when the universe was younger.

Hubble's Galaxy Classes Edwin Hubble invented a system for classifying galaxies that organizes the galaxy types into a diagram shaped like a tuning fork (Figure 15.7). Elliptical galaxies appear on the "handle" at the left, designated by the letter *E* and a number. The larger the number, the flatter the elliptical galaxy: An E0 galaxy is a sphere, and the numbers increase to the highly elongated type E7. The two forks show spiral galaxies, designated by the letter *S* for ordinary spirals and *SB* for barred spirals, followed by a lowercase *a*, *b*, or *c*: The bulge size decreases from *a* to *c*, while the amount of dusty gas increases. Lenticular galaxies are designated S0, and irregular galaxies are designated Irr.

Astronomers had once hoped that the classification of galaxies might yield deep insights, just as the classification of stars did in the early twentieth century. The Hubble classification scheme itself was suspected for a time to be an evolutionary sequence in which galaxies flattened and spread out as they aged. Unfortunately for astronomers, galaxies turn out to be far more complex than stars, and classification schemes like this one have not led to any major insights into their nature.

Figure 15.6

The Large Magellanic Cloud, an irregular galaxy that is a small companion to the Milky Way. It is about 30,000 light-years across.

• How are galaxies grouped together?

Most of the galaxies in the universe are gravitationally bound together with neighboring galaxies. Spiral galaxies are often found in loose collections of up to a few dozen galaxies, called groups. Our

Figure 15.7

This "tuning fork" diagram illustrates Hubble's galaxy classes.

Figure 15.8

Hickson Compact Group 87, a small group of galaxies consisting of a large edge-on spiral galaxy (bottom), two smaller spiral galaxies (center and upper left), and an elliptical galaxy (right). The whole group is about 170,000 light-years in diameter. (The other objects in this photograph are foreground stars in our own galaxy.)

Local Group is one example (see Figure 1.1). Figure 15.8 shows another galaxy group.

Spiral galaxies tend to congregate in small groups, while elliptical galaxies are primarily found in large clusters.

Elliptical galaxies are particularly common in clusters of galaxies, which can contain hundreds to thousands of galaxies extending over more than 10 million light-years (Figure 15.9). Elliptical galaxies make up about half the large galaxies in the central regions of clusters, while they represent only a small minority (about 15%) of the large galaxies found outside clusters.

MA Measuring Cosmic Distances Tutorial, Lessons 1–4

15.2 Distances of Galaxies

To learn more about galaxies than just their shape, color, and type, we need to know how far away they are. Measuring the distances to galaxies is one of the most challenging tasks we face when trying to understand galaxies and the universe as a whole, but the payoff is enormous. Besides telling us where galaxies are located, such measurements also reveal the size and age of the observable universe.

• How do we measure the distances to galaxies?

Our determinations of astronomical distances depend on a chain of methods in which each step allows us to measure greater distances in the universe. We have already discussed the measurement of distances to nearby stars by parallax **[Section 11.1]**. Because parallax is the apparent shift in a star's position as Earth orbits the Sun, measuring distances by parallax requires knowing the precise Sun–Earth distance, or astronomical unit (AU). Astronomers measure the AU with a technique called **radar ranging**, in which radio waves are transmitted from Earth and bounced off Venus. Radio waves travel at the speed of light, so the round-trip travel time for the radar signals tells us Venus's distance from Earth. We can then use Kepler's laws and a little geometry to calculate the length of an AU. Radar ranging measurements of the AU represent the first link in the distance chain, and parallax measurements of distances to nearby stars represent the second link. We will now follow the rest of this chain, link by link, to the outermost reaches of the observable universe.

Figure 15.9

Central part of the galaxy cluster Abell 1689. Almost every object in this photograph is a galaxy belonging to the cluster. Yellowish elliptical galaxies outnumber the whiter spiral galaxies. The region pictured is about 2 million light-years across. (A few stars from our own galaxy appear in the foreground and look like white dots with four spikes in the form of a cross.)

Standard Candles Once we have measured distances to nearby stars through parallax, we can begin to measure distances to other stars in the same way that we might estimate the distance to a street lamp at night. If the street lamp does not look very bright, then it's probably far away. If it looks very bright, then it's probably nearby.

We can determine distance by measuring the apparent brightness of an object whose luminosity we already know and applying the inverse square law for light.

We can determine the lamp's distance more accurately if we can measure its apparent brightness. For example, suppose we see a distant street lamp and know that every street lamp of its type emits 1000 watts of light. If we then measure its apparent brightness, we can calculate its distance using the inverse square law for light **[Section 11.1]**.

An object such as a street lamp, for which we are likely to know the true luminosity, represents what astronomers call a **standard candle**—a

light source of a known, standard luminosity. Unlike light bulbs, however, astronomical objects do not come marked with wattage. An astronomical object can serve as a standard candle only if we have some way of knowing its true luminosity without first measuring its apparent brightness and distance. Fortunately, many astronomical objects meet this requirement. For example, any star that is a twin of our Sun—that is, a main-sequence star with spectral type G2—should have about the same luminosity as the Sun. If we measure the apparent brightness of a Sun-like star, we can assume it has the same luminosity as the Sun and use the inverse square law for light to estimate its distance.

Beyond the few hundred light-years for which we can measure distances by parallax, we use standard candles for most cosmic distance measurements. These distance measurements always have some uncertainty, because no astronomical object is a perfect standard candle. The challenge of measuring astronomical distances comes down to the challenge of finding the objects that make the best standard candles. The more confidently we know an object's true luminosity, the more certain we are of its distance.

Main-Sequence Fitting Although Sun-like stars are reasonably good standard candles, they are of limited use because Sun-like stars are relatively dim, making them difficult to detect beyond relatively short distances. To measure distances beyond 1000 light-years or so, we need brighter standard candles.

Brighter main-sequence stars represent an obvious first choice, because all main-sequence stars of a particular spectral type have about the same luminosity **[Section 11.2]**. However, before we can use any main-sequence star as a standard candle, we must first have some way of knowing its true luminosity. We therefore need to follow two steps to use bright main-sequence stars as standard candles:

1. We identify a star cluster that is close enough for us to determine its distance by parallax and plot its H-R diagram. Because we know the distances to the cluster stars, we can use the inverse square law for light to establish their true luminosities from their apparent brightnesses.
2. We can look at stars in other clusters that are too far away for parallax measurements and measure their apparent brightnesses. If we assume that main-sequence stars in other clusters have the same luminosities as their counterparts in the nearby cluster, we can calculate their distances from the inverse square law for light.

Twentieth-century astronomers laid the groundwork for this technique by calibrating the luminosities on an H-R diagram. This calibration relied largely on a single, nearby star cluster—the Hyades Cluster in the constellation Taurus, whose distance is now known from its parallax. We can find the distances to other star clusters by comparing the apparent brightnesses of their main-sequence stars with those in the Hyades Cluster and assuming that all main-sequence stars of the same color have the same luminosity (Figure 15.10). This technique of determining distances by comparing main sequences in different star clusters is called **main-sequence fitting**.

Cepheid Variables Main-sequence fitting works well for measuring distances to star clusters throughout the Milky Way, but not for measuring distances to other galaxies. Most main-sequence stars are too faint to be seen in other galaxies, even with our largest telescopes. Instead, we need

cosmic Calculations 15.1

Standard Candles

The inverse square law for light tells us how an object's apparent brightness depends on its luminosity and distance (see Cosmic Calculations 11.1). With a little algebra, we can rewrite this law in a form that enables us to calculate distance if we know luminosity and apparent brightness, as we do for any object that qualifies as a *standard candle*.

$$\text{distance} = \sqrt{\frac{\text{luminosity}}{4\pi \times (\text{apparent brightness})}}$$

For a standard candle of a particular luminosity, the formula tells us that a smaller apparent brightness means a greater distance.

Example: You observe a main-sequence star of spectral type G2, measuring its apparent brightness to be 1.0×10^{-12} watt/m^2. How far away is it?

Solution: The star has the same spectral type as our Sun, so we assume that its luminosity is approximately equal to the Sun's luminosity of 3.8×10^{26} watts. We use this luminosity and the star's apparent brightness in the formula:

$$\text{distance} = \sqrt{\frac{3.8 \times 10^{26}\ \text{watts}}{4\pi \times \left(1.0 \times 10^{-12}\ \frac{\text{watt}}{\text{m}^2}\right)}} \approx 5.5 \times 10^{18}\ \text{m}$$

The distance to the star is about 5.5×10^{18} m. When we divide this distance by 9.5×10^{16} m/ly, we find that it is equivalent to about 580 light-years. Of course, if the star's actual luminosity is different from the Sun's, the distance we found will also be in error.

Figure 15.10

To use the technique of main-sequence fitting, we compare the apparent brightness of the main sequence of a cluster of unknown distance (the Pleiades, in this case) to that of a cluster whose distance we already know (such as the Hyades, whose distance is known from parallax).

very bright stars to serve as standard candles for distance measurements beyond the Milky Way.

The most useful bright stars for measuring the distances to galaxies are called **Cepheid variable stars**, or **Cepheids** for short. These stars vary in brightness in our sky, alternately becoming dimmer and brighter with periods ranging from a few days to a few months. Each Cepheid has its own particular time period between peaks in luminosity. Figure 15.11 shows the brightness variations of a Cepheid with a period of about 50 days.

Cepheid variable stars are useful for measuring distances because we can determine a Cepheid's luminosity from the period between its peaks of brightness.

In 1912, Henrietta Leavitt discovered that the periods of Cepheids are very closely related to their luminosities: The longer the period, the more luminous the star (Figure 15.12). We say that Cepheids obey a **period–luminosity relation** that allows us to determine (within about 10%) a Cepheid's luminosity simply by measuring the time period over which its brightness varies. Figure 15.12 shows that a Cepheid variable whose brightness peaks every 30 days is effectively screaming out, "Hey, everybody, my luminosity is 10,000 times that of the Sun!" Once we measure a Cepheid's period, we know its luminosity and we can use the inverse square law for light to determine its distance.

Leavitt discovered the period–luminosity relation with careful observations of Cepheids in the Magellanic Clouds but she did not know why Cepheids vary in this special way. We now know that Cepheids vary because they have a peculiar problem in matching the amount of energy their surfaces radiate with the amount welling up from the core. In a futile quest for a steady equilibrium, the upper layers of a Cepheid variable star alternately expand and contract, causing the star's luminosity to rise and fall. The period–luminosity relation holds because larger (more luminous) Cepheids take longer to pulsate in and out in size.

Cepheids have been used for almost a century to measure distances to nearby galaxies. As we'll discuss shortly, they played a critical role in Edwin Hubble's discoveries. More recently, one of the main missions of the Hubble Space Telescope was to measure accurate distances to galaxies

Figure 15.11

This graph shows how the brightness of a Cepheid varies with time. The period is the time from one peak of brightness to the next.

Figure 15.12

Cepheid period–luminosity relation. The data show that all Cepheids of a particular period have very nearly the same luminosity. Measuring a Cepheid's period therefore allows us to determine its luminosity and calculate its distance. (Cepheids actually come in two types with two different period–luminosity relations. The relation here is for Cepheids with heavy-element content similar to that of our Sun, or Type I Cepheids.)

up to 100 million light-years away by studying Cepheids within them. This distance may sound very large, but it is still quite small compared with the distances of the galaxies in Figure 15.1. To go further, we use the distances determined with these Cepheids to learn the luminosities of even brighter standard candles.

Distant Standard Candles Astronomers have discovered several techniques for estimating distances beyond those for which we can observe Cepheids. The most valuable of these techniques has proved to be the use of white dwarf supernovae as standard candles. Recall that white dwarf supernovae are thought to be exploding white dwarf stars that have reached the $1.4M_{\text{Sun}}$ limit **[Section 13.1]**. These supernovae should all have nearly the same luminosity, because they all come from stars of the same mass that explode in the same way. Although white dwarf supernovae are rare in any individual galaxy, several have been detected during the past century in galaxies within about 50 million light-years of the Milky Way. Astronomers kept careful records of those events, so that today we can determine the true luminosities of these supernovae by using Cepheids to measure the distances to the galaxies in which they occurred. These measurements confirm that the luminosities of all white dwarf supernovae are about the same.

White dwarf supernovae are useful for measuring large distances because they are bright and all have about the same peak luminosity.

Because white dwarf supernovae are so bright—about 10 billion solar luminosities at their peak—we can detect them even when they occur in galaxies billions of light-years away (Figure 15.13). We can therefore use them to measure the distances of galaxies in the far reaches of the observable universe, completing the distance chain. Although the number of galaxies whose distances we can measure with this technique is relatively small, because white dwarf supernovae occur only once every few hundred years in a typical galaxy, these galaxies have allowed us to calibrate another technique—one that relies on the expansion of the universe.

MA Hubble's Law Tutorial, Lessons 1–3

• What is Hubble's law?

The ability to measure distances to galaxies is the key to much of our modern understanding of the size and age of the universe. We can trace the beginning of this understanding directly back to discoveries made by Edwin Hubble. Let's explore how Hubble discovered the famous law that bears his name and how this law has helped us answer fundamental questions about the universe in which we live.

Edwin Hubble and the Andromeda Galaxy Before Edwin Hubble's groundbreaking work in the 1920s, no one knew for certain whether the spiral-shaped objects they saw in the sky were merely clouds of gas within the Milky Way—and therefore that the Milky Way represented the entire universe—or distant and distinct galaxies. The opinions of astronomers were split on this issue, which became a subject of great debate. The problem was that neither side could prove its case, because the techniques available at the time could not distinguish objects within the Milky Way from those beyond it.

Figure 15.13

White dwarf supernovae in galaxies approximately 10 billion light-years away. White arrows in the lower images indicate the supernovae, and the upper images show what these galaxies looked like without supernovae.

Figure 15.14

Edwin Hubble at the Mount Wilson Observatory.

Figure 15.15

Redshifted galaxy spectrum.

Hubble put the debate to rest in 1924. Using the new, 100-inch telescope atop southern California's Mount Wilson (Figure 15.14)—the largest telescope in the world at the time—he identified Cepheid variables in the Andromeda Galaxy by comparing photographs of the galaxy taken days apart. He then used those Cepheid observations and Henrietta Leavitt's period–luminosity relation to estimate the galaxy's distance, proving that the Andromeda Galaxy resides far beyond the outer reaches of the Milky Way.

Edwin Hubble used Cepheids to prove that the Andromeda Galaxy lies beyond the Milky Way.

This single scientific discovery dramatically changed our view of the universe. Rather than thinking the Milky Way was the entire universe, we suddenly knew that it is just one among many galaxies in an enormous universe. The stage was set for an even greater discovery.

Distance and Redshift Astronomers had known since the 1910s that the spectra of most spiral galaxies tended to be *redshifted* (Figure 15.15). Recall that redshifts occur when the object emitting the radiation is moving away from us **[Section 5.2]**. Because Hubble had not yet proved that the spiral galaxies were separate from the Milky Way, no one understood the true significance of their motions.

Following his discovery of Cepheids in Andromeda, Hubble and his coworkers spent the next few years measuring the redshifts of galaxies and estimating their distances. Because even Cepheids were too dim to be seen in most of these galaxies, Hubble needed brighter standard candles for his distance estimates. One of his favorite techniques was to use the brightest object he could see in each galaxy as a standard candle, because he assumed these objects to be very bright stars that would always have about the same luminosity.

A galaxy's redshift tells us how fast it is moving away from us, and the relationship between redshift and distance shows that the universe is expanding.

In 1929, Hubble announced his conclusion: The more distant a galaxy, the greater its redshift and hence the faster it moves away from us. As we discussed in Chapter 1 (see Figure 1.15), this discovery implies that the entire universe is expanding. Thus, Hubble discovered the expansion of the universe.

Hubble's original assertion was based on an amazingly small sample of galaxies. Even more incredibly, he had grossly underestimated the luminosities of his standard candles. The "brightest stars" he had been using as standard candles were really entire *clusters* of bright stars. Fortunately, Hubble was both bold and lucky. Subsequent studies of much larger samples of galaxies showed that they are indeed receding from us, but they are even farther away than Hubble thought.

Hubble's Law We express the idea that more distant galaxies move away from us faster with a very simple formula, now known as **Hubble's law**:

$$v = H_0 \times d$$

where v stands for a galaxy's velocity away from us (sometimes called the *recession velocity*), d stands for its distance, and H_0 (pronounced "H-naught") is a number called **Hubble's constant**. We usually write Hubble's law in this form to express the idea that the speed of a galaxy depends on its distance from us. However, astronomers more often use the law in

reverse—measuring a galaxy's speed from its redshift and then using Hubble's law to estimate its distance.

Hubble's law expresses a relationship between galaxy speeds and distances, and hence allows us to determine a galaxy's distance from its speed.

Because Hubble's law in principle applies to all distant galaxies for which we can measure a redshift, it is the most useful technique for determining distances to galaxies that are very far away. Nevertheless, we encounter two practical difficulties when we try to use Hubble's law to measure galactic distances:

1. Galaxies do not obey Hubble's law perfectly. Hubble's law gives an exact distance only for a galaxy whose speed is determined solely by the expansion of the universe. In reality, nearly all galaxies experience gravitational tugs from other galaxies, and these tugs alter their speeds from the values predicted by Hubble's law.
2. Even when galaxies obey Hubble's law well, the distances we find with it are only as accurate as our best measurement of Hubble's constant.

The first problem is most serious for nearby galaxies. Within the Local Group, for example, Hubble's law does not work at all: The galaxies in the Local Group are gravitationally bound together with the Milky Way and therefore are *not* moving away from us in accord with Hubble's law. However, Hubble's law works well for more distant galaxies, which have recession velocities so great that any motions caused by the gravitational tugs of neighboring galaxies are tiny in comparison.

The second problem means that, even for distant galaxies, we can know only *relative* distances until we pin down the true value of H_0. For example, Hubble's law tells us that a galaxy moving away from us at 20,000 km/s is twice as far away as one moving at 10,000 km/s, but we can determine the actual distances of the two galaxies only if we know H_0.

The quest to measure Hubble's constant was one of the main missions of the Hubble Space Telescope.

The Hubble Space Telescope has helped us obtain an accurate value of H_0. Astronomers used the telescope to find Cepheid variables in galaxies out to about 60 million light-years and then used those distances to determine the luminosities of distant standard candles such as white dwarf supernovae. Plotting galactic distances measured with those distant standard candles against the velocities indicated by their redshifts has pinned down the value of H_0 to somewhere between 21 and 23 *kilometers per second per million light-years* (Figure 15.16). That is, a galaxy's speed away from us is between 21 and 23 km/s for every million light-years it is from us. For example, with this range of values for Hubble's constant, Hubble's law predicts that a galaxy located 100 million light-years away would be moving away from us at a speed between 2100 and 2300 km/s.

Distance Chain Summary Figure 15.17 summarizes the chain of measurements that allows us to determine ever greater distances. However, each link in the distance chain adds more uncertainty to the estimated distance. As a result, although we know the Earth–Sun distance at the beginning of the chain extremely accurately, distances to the farthest reaches of the observable universe remain uncertain by about 10%.

cosmic Calculations 15.2

Hubble's Law

Page 420 shows Hubble's law written $v = H_0 \times d$. However, astronomers usually measure a galaxy's recession velocity v, then use the law to calculate the galaxy's distance d. To do this, it's more useful to divide both sides of the law by Hubble's constant H_0 to put it in the form

$$d = \frac{v}{H_0}$$

In this form, we can calculate a galaxy's distance in light-years if we have its measured velocity in kilometers per second and Hubble's constant in units of *kilometers per second per million light-years* (km/s/Mly).

Example: Estimate the distance to a galaxy whose redshift indicates that it is moving away from us at a speed of 22,000 km/s. Assume that Hubble's constant is $H_0 = 22$ km/s/Mly.

Solution: Putting the given values into our formula, we find

$$d = \frac{v}{H_0} = \frac{22{,}000 \text{ km/s}}{22 \ \frac{\text{km/s}}{\text{Mly}}} = 1000 \text{ Mly}$$

The galaxy's distance is 1000 million light-years, which is the same as 1 billion light-years.

Figure 15.16 MA interactive figure

We use data from white dwarf supernovae to determine Hubble's law and to make our best estimate of Hubble's constant. The points on the graph show the apparent distances of white dwarf supernovae and the recession velocities of the galaxies in which they exploded. The fact that these points all fall close to a straight line demonstrates that these supernovae are good standard candles.

Figure 15.17 MA interactive figure

Measurement of cosmic distances relies on a chain of interlocking techniques. The chain begins with radar ranging to determine distances within our solar system and proceeds through parallax and standard candle techniques. The use of these techniques allows us to calibrate Hubble's law, which we can then use to estimate distances to galaxies across the observable universe.

- **Radar ranging:** We measure the Earth–Sun distance by bouncing radio waves off Venus and using some geometry.
- **Parallax:** We measure the distances to nearby stars by observing how their positions appear to change as Earth orbits the Sun. These distances rely on our knowledge of the Earth–Sun distance, determined with radar ranging.
- **Main-sequence fitting:** We know the distance to the Hyades star cluster in our Milky Way Galaxy through parallax. Comparing the apparent brightnesses of its main-sequence stars to those of stars in other clusters gives us the distances to these other star clusters in our galaxy.
- **Cepheid variables:** By studying Cepheids in star clusters with distances measured by main-sequence fitting, we learn the precise period–luminosity relation for Cepheids. When we find a Cepheid in a more distant star cluster or galaxy, we can determine its true luminosity by measuring the period between its peaks in brightness and then use this true luminosity to determine the distance.
- **Distant standards:** By measuring distances to relatively nearby galaxies with Cepheids, we learn the true luminosities of white dwarf supernovae and other distant standard candles, enabling us to measure great distances throughout the universe.
- **Hubble's law:** Distances measured to galaxies with white dwarf supernovae and other distant standards allow us to measure Hubble's constant, H_0. Once we know H_0, we can use Hubble's law to determine a galaxy's distance from its redshift.

• How do distance measurements tell us the age of the universe?

Hubble's law is a remarkably powerful tool for understanding the universe. Not only does it tell us that the universe is expanding and give us a way to measure galactic distances, but it also helps us determine the age and size of the observable universe. To see how, we must first consider the expansion of the universe in a little more detail.

Universal Expansion Galaxies all across the universe are moving away from one another, and this fact implies that galaxies must have been closer together in the past. Tracing this convergence back in time, we reason that all the matter in the observable universe started very close together and that the entire universe came into being at a single moment—the Big Bang **[Section 1.1]**.

The expansion of the universe implies that the universe came into being at a single moment in time.

It may be tempting to think of the expanding universe as a ball of galaxies expanding into a void, but this impression is mistaken. To the best of our knowledge, the universe is not expanding into anything. As far as we can tell, there is no edge to the distribution of galaxies in the universe. On very large scales, the distribution of galaxies appears to be relatively smooth, meaning that the overall appearance of the universe around you would look more or less the same no matter where you were located. The idea that the matter in the universe is evenly distributed, without a center or an edge, is often called the **Cosmological Principle**. Although we cannot prove it to be true, it is consistent with all our observations of the universe **[Section 16.3]**.

So how can the universe be expanding if it's not expanding into anything? Back in Chapter 1, we likened the expanding universe to a raisin cake baking **[Section 1.3]**, but a cake has a center and edges that grow into empty space as it bakes. A better analogy is something that can expand but that has no center and no edges. The surface of a balloon can fit the bill, as can an infinite surface such as a sheet of rubber that extends to infinity in all directions.

Because it's hard to visualize infinity, let's use the surface of a balloon in our analogy to the expanding universe (Figure 15.18). Note that this analogy uses the balloon's two-dimensional surface to represent all three dimensions of space. The surface of the balloon represents the entire universe, and the spaces inside and outside the balloon have no meaning in this analogy. Aside from the reduced number of dimensions, the analogy works well because the balloon's spherical *surface* has no center and no edges. We can represent galaxies with plastic polka dots attached to the balloon, and we can make our model universe expand by inflating the balloon.

see it for yourself Make a one-dimensional model of the expanding universe with a rubber band and some paper clips. Cut the rubber band so you can stretch it out along a line, then attach four paper clips along it. Pin down the ends of the rubber band and measure the distances from one paper clip to each of the others. Then unpin one of the ends, stretch the rubber band more, pin it down again, and remeasure the distances. How much have they changed? How do your measurements illustrate Hubble's law?

The Age of the Universe We can now see how Hubble's law leads us to an age for the universe. Imagine that some miniature scientists are living

Figure 15.18 MA interactive figure

As the balloon expands, dots move apart in the same way that galaxies move apart in our expanding universe.

common Misconceptions

What Is the Universe Expanding Into?

When you first learn about expansion of the universe, it's natural to assume that the universe must be expanding "into" something. After all, the name "Big Bang" makes the event that triggered the expansion seem like a huge explosion that sent matter flying outward into a vast space that was previously empty. However, the scientific view of the Big Bang is very different. According to modern science, the Big Bang filled *all of space* with matter and energy.

How can the Big Bang have started "all of space" expanding without it expanding into some empty void? A complete answer requires Einstein's general theory of relativity, which tells us that space can be "curved" in ways we can measure but cannot visualize (see Special Topic, p. 372). But you can understand the key ideas with the balloon analogy. Remember that the balloon's *surface* represents all of space; just as the surface has no center and no edges, space has no center and no edges. In the analogy, the expanding universe is like the expanding surface of the balloon, and the Big Bang was the moment when an extremely tiny balloon first started growing in size. As the balloon expands, any two points on the surface get farther apart because the surface itself is stretching, not because they are moving into a previously empty region above the surface. In the same way, galaxies move apart in the expanding universe because the space between them is stretching, not because they move into a space that was previously empty.

on Dot B in Figure 15.18. Suppose that, 3 seconds after the balloon begins to expand, they measure the following:

Dot A is 3 cm away and moving at 1 cm/s.
Dot C is 3 cm away and moving at 1 cm/s.
Dot D is 6 cm away and moving at 2 cm/s.

They could summarize these observations as follows: *Every dot is moving away from our home with a speed that is 1 cm/s for each 3 cm of distance.* Because the expansion of the balloon is uniform, scientists living on any other dot would come to the same conclusion. Each scientist living on the balloon would determine that the following formula relates the distances and velocities of other dots on the balloon:

$$v = \left(\frac{1}{3\,\mathrm{s}}\right) \times d$$

where v and d are the velocity and distance of any dot, respectively.

think about it Confirm that this formula gives the correct values for the speeds of Dots C and D, as seen from Dot B, 3 seconds after the balloon began expanding. How fast would a dot located 9 cm from Dot B move, according to the scientists on Dot B?

If the miniature scientists think of their balloon as a bubble, they might call the number relating distance to velocity—the term $\frac{1}{3\,\mathrm{s}}$ in the preceding formula—the "bubble constant." An especially insightful miniature scientist might flip over the "bubble constant" and find that it is exactly equal to the time elapsed since the balloon started expanding. That is, the "bubble constant" $\frac{1}{3\,\mathrm{s}}$ tells them that the balloon has been expanding for 3 seconds. Perhaps you see where we are heading.

Just as the inverse of the "bubble constant" tells the miniature scientists that their balloon has been expanding for 3 seconds, the inverse of the Hubble constant, or $\frac{1}{H_0}$, tells us something about how long our universe has been expanding. The "bubble constant" for the balloon depends on when it is measured, but it is always equal to 1 divided by the time elapsed since the balloon started expanding. Similarly, the Hubble constant actually changes with time but stays roughly equal to 1 divided by the age of the universe. We call it a constant because it is the same at all locations in the universe at a particular moment in time, and because its value does not change noticeably on the time scale of human civilization.

The rate at which the universe expands tells us how old it is—about 14 billion years.

Current estimates based on the value of Hubble's constant put the age of the universe between about 12 and 15 billion years. To derive a more precise value for the universe's age, we need to know whether the expansion has been speeding up or slowing down over time, a question we will examine more closely in Chapter 16. If the gravitational pull of each galaxy on every other galaxy has significantly slowed the expansion rate, then the universe's age is somewhat less than $\frac{1}{H_0}$. If some mysterious force has accelerated the expansion rate, then the universe's age is somewhat more than $\frac{1}{H_0}$. The best available evidence suggests that the universe is about 14 billion years old.

Lookback Time The expansion of the universe leads to a complication in discussing galaxy distances that we have ignored up to this point. Imagine observing a supernova in a distant galaxy. Suppose the supernova occurred 400 million years ago but we are only just now

seeing it. The supernova's light must have traveled 400 million light-years to reach Earth, but this simple statement about how far the light has traveled does not translate easily into a distance for the galaxy in which the supernova occurred. The problem is that the universe is expanding, making the distance between Earth and the supernova greater today than it was at the time of the supernova event. If we simply say that the galaxy is "400 million light-years away," it's not clear whether we mean its distance now, its distance at the time of the supernova, or something in between.

An object's lookback time is the time it took for the object's light to reach us.

Because distances between galaxies are always changing, it is easier to speak about faraway objects in terms of how much time their light takes to reach us—400 million years in the case of the supernova. We call this the **lookback time** to the supernova. In other words, a distant object's lookback time is the difference between the current age of the universe and the age of the universe when the light left the object. Unlike a statement about distance, the meaning of a lookback time is unambiguous: If the lookback time is 400 million years, it means the light traveled through space for a period of 400 million years to reach us.

An object's lookback time is directly related to its redshift. Recall that the redshifts of galaxies tell us how quickly they are moving away from us. In the context of an expanding universe, redshifts have an additional, more fundamental interpretation. Let's return again to the balloon universe. Suppose you draw wavy lines on the balloon's surface to represent light waves. As the balloon inflates, these wavy lines stretch out, and their wavelengths increase (Figure 15.19). This stretching closely resembles what happens to photons in an expanding universe. The expansion of the universe stretches out all the photons within it, shifting them to longer, redder wavelengths. We call this effect a **cosmological redshift.**

In a sense, we have a choice when we interpret the redshift of a distant galaxy: We can think of the redshift either as being caused by the Doppler effect as the galaxy moves away from us or as being a cosmological redshift due to the photon-stretching expansion of the universe. However, as we look to very distant galaxies, the ambiguity in the meaning of *distance* also makes it difficult to specify precisely what we mean by a galaxy's *speed.* Thus, it becomes preferable to interpret the redshift as being due to photon stretching in an expanding universe.

From this perspective, it is better to think of space itself as expanding, carrying the galaxies along for the ride, than to think of the galaxies as projectiles flying through a static universe. The cosmological redshift of a galaxy therefore tells us how much space has expanded during the time since light from the galaxy left on its journey to us.

Figure 15.19 MA interactive figure

As the universe expands, photon wavelengths stretch like the wavy lines on this expanding balloon.

The Horizon of the Universe

When we began our discussion of the expanding universe, we stressed that the universe as a whole does not seem to have an edge. However, the universe does have a *horizon* beyond which we cannot see. The **cosmological horizon** that marks the limits of the observable universe is a boundary in time, not in space.

The size of the observable universe is determined by the age of the universe.

Our quest to study galaxies and measure their distances has brought us to the very limits of the observable universe. As we discussed in Chapter 1, the age of the universe limits the size of our observable universe (see Figure 1.4): In a universe that is 14 billion years old, we cannot see any object with a lookback time greater than 14 billion years.

common Misconceptions

Beyond the Horizon

Perhaps you're thinking there must be something beyond the cosmological horizon. After all, we can see farther and farther with each passing second. The new matter we see had to come from somewhere, didn't it? The problem with this reasoning is that the cosmological horizon, unlike a horizon on Earth, is a boundary in time, not in space.

At any one moment, in whatever direction we look, the cosmological horizon lies at the beginning of time and encompasses a certain volume of the universe. At the next moment, the cosmological horizon still lies at the beginning of time, but it encompasses a slightly larger volume. When we peer into the distant universe, we are looking back in both space and time. We cannot look "past the horizon" because we cannot look back to a time before the universe began.

15.3 Galaxy Evolution

Now that we understand how galactic distances are measured, we are ready to turn our attention back to understanding galaxies themselves. We understand less about the formation and development of galaxies, or **galaxy evolution**, than we do about the lives of stars. Nevertheless, we've made great progress in understanding galaxy evolution in recent decades, thanks largely to the same powerful telescopes that have allowed us to measure distances more accurately.

• How do we observe the life histories of galaxies?

Powerful telescopes can be used like time machines to observe the life histories of galaxies—the farther we look into the universe, the further back we look in time **[Section 1.1]**. The most distant galaxies already had some stars in place by about 13 billion years ago, which means these stars match the ages of the oldest stars in our own galaxy. It therefore seems safe to assume that most galaxies began to form at about this time, in which case most galaxies would be roughly the same age today. A galaxy's lookback time is therefore linked directly to its age. Most of the galaxies we see nearby are around 13 billion years old. Observations of galaxies with a lookback time of 10 billion years show us what they were like when they were no more than 3 billion years old.

Images of the deep universe allow us to study galaxies at many different distances and therefore many different ages.

The linkage between a galaxy's distance and its age gives us a remarkable ability: Simply by photographing galaxies at different distances, we can assemble "family albums" showing them in different stages of development. Pictures of the farthest galaxies show them in their childhood, and pictures of the nearest show mature galaxies as they are today. Figure 15.20 shows partial family albums for elliptical, spiral, and irregular galaxies. Each individual photograph shows a single galaxy at a single stage in its life. Grouping these photographs by galaxy type allows us to see how galaxies of a particular type have changed through time.

think about it In the preceding paragraph, we use the term *today* in a very broad sense. For example, if we look at a relatively nearby galaxy—one located, say, 20 million light-years away—we see it as it was 20 million years ago. In what sense is this "today"? (*Hint*: How does 20 million years compare to the age of the universe? To the lifetime of a massive star?)

The photographs in Figure 15.20, taken by the Hubble Space Telescope, show galaxies extending back to a time when the universe was just 1 or 2 billion years old. However, the first stars and galaxies appear to have formed even earlier than this. Observing these first stars and galaxies is a challenge not even Hubble can meet. Detecting such faraway galaxies will require larger telescopes, and the extreme redshifts expected for such galaxies mean the telescopes will need to be particularly sensitive to infrared light. NASA is currently building a new telescope with these capabilities, called the James Webb Space Telescope; with luck, it could be launched as early as 2014.

• How did galaxies form?

Because our telescopes cannot yet see back to the birth of galaxies, we must use theoretical models to learn about galaxy formation. The most successful models assume the following:

Figure 15.20

Family albums for elliptical, spiral, and irregular galaxies of different ages, plus some very young galaxies shown on the far left. These photos are all zoomed-in images of galaxies from the Hubble Ultra Deep Field, a portion of which is shown on page 1. We see more distant galaxies as they were when they were younger, indicated by the approximate age of the universe along the horizontal axis.

- Hydrogen and helium gas filled all of space more or less uniformly when the universe was very young—say, in the first million years after its birth.
- The distribution of matter in the universe was not perfectly uniform—certain regions of the universe started out slightly more dense than others.

Beginning with these assumptions, which a mounting body of evidence supports **[Section 17.2]**, we can model galaxy formation using well-established laws of physics to trace how the denser regions in the early universe grew into galaxies (Figure 15.21). The models show that the regions of enhanced density originally expanded along with the rest of the universe. However, the slightly greater pull of gravity in these regions gradually slowed their expansion. Within about a billion years, the expansion of these denser regions halted and reversed, and the material within them began to contract into *protogalactic clouds* like the cloud of matter that eventually formed our Milky Way **[Section 14.3]**.

Our most successful models of galaxy formation suggest that protogalactic clouds formed in regions of slightly enhanced density in the early universe.

According to the models, the protogalactic clouds that eventually formed spiral galaxies initially cooled as they contracted, radiating away their thermal energy, and the

Figure 15.21 MA interactive figure

A computer simulation of the formation of protogalactic clouds. The simulated region of space is about 500 million light-years wide and will go on to form numerous galaxies.

first generation of stars grew from the densest, coldest clumps of gas. These first-generation stars were probably quite massive, living and dying within just a few million years—a short time compared to the time required for the collapse of a protogalactic cloud into a spiral disk. The supernovae of these massive stars seeded each collapsing cloud with its first sprinkling of heavy elements and generated shock waves that heated the surrounding interstellar gas. This heating slowed the collapse of the protogalactic clouds and the rate at which stars formed within them, allowing time for the rest of the gas in each newly forming galaxy to settle into a rotating disk.

This picture explains many of the basic features of galaxies. In particular, it explains why other spiral galaxies have the same basic structure as the Milky Way: a *disk population* of stars that orbit the galactic center in a fairly flat plane and a *spheroidal population* of stars with more randomly oriented orbits (see Figure 14.2). The spheroidal population consists of stars that were born before the galaxy's rotation became organized, which is why they have orbits oriented in many different ways around the galactic center. The disk population consists of stars born after the gas in the protogalactic cloud settled into a rotating disk, which is why they all have similar orbits around the center of the galaxy (see Figure 14.18).

However, this basic picture leaves at least two major questions unanswered. First, our models assume that galaxies formed in regions of slightly enhanced density, but they do not tell us where these density enhancements came from. The origin of density enhancements in the early universe is one of the major puzzles in astronomy; we'll revisit it in Chapters 16 and 17. Second, our basic picture explains the origin of spiral galaxies quite well, but it does not tell us why some galaxies are elliptical and others irregular. That is the question to which we turn our attention next.

• Why do galaxies differ?

All protogalactic clouds are thought to have begun in the same basic way, with gravity collecting matter around a pre-existing density enhancement. How, then, did galaxies end up in the different types we see today? Our models suggest two possibilities: (1) Galaxies may have ended up looking different because they began with slightly different conditions in their protogalactic clouds, or (2) galaxies may have begun their lives similarly but later changed due to interactions with other galaxies. To help differentiate the role of conditions in the protogalactic cloud from that of subsequent interactions, we will explore a single key question: Why do spiral galaxies have gas-rich disks, while elliptical galaxies do not?

Conditions in the Protogalactic Cloud Two plausible explanations for the differences between spiral galaxies and elliptical galaxies trace a galaxy's type back to the protogalactic cloud from which it formed:

- **Protogalactic spin.** A galaxy's type might be determined by the spin of the protogalactic cloud from which it formed. If the original cloud had a significant amount of angular momentum, it would have rotated quickly as it collapsed. The galaxy it produced would therefore have tended to form a disk, and the resulting galaxy would be a spiral. If the protogalactic cloud had little or no angular momentum, its gas might not have formed a disk at all, and the resulting galaxy would be elliptical.
- **Protogalactic density.** A galaxy's type might be determined by the density of the protogalactic cloud from which it formed. A

protogalactic cloud with relatively high gas density would have radiated energy more effectively and cooled more quickly, thereby allowing more rapid star formation. If the star formation proceeded fast enough, all the gas could have been turned into stars before any of it had time to settle into a disk, making it an elliptical galaxy. In contrast, a lower-density cloud would have formed stars more slowly, leaving plenty of gas to form the disk of a spiral galaxy.

Elliptical galaxies may have formed from protogalactic clouds that were spinning more slowly or were denser than those that formed spiral galaxies.

Evidence for the latter scenario comes from a few giant elliptical galaxies at very great distances. These galaxies look very red even after we have accounted for their large redshifts. They apparently have no blue or white stars at all, indicating that new stars no longer form within these galaxies—even though we are seeing them as they were when the universe was only a few billion years old. This finding suggests that all the stars in these elliptical galaxies were born at almost the same time, which is consistent with the idea that all the stars formed before a disk could develop.

Galactic Collisions The two previous scenarios, in which the formation of a gas-rich disk depends on the angular momentum or density of the protogalactic cloud, probably describe important parts of the overall story. However, they ignore one key fact: Galaxies rarely evolve in isolation.

Think back to our scale model solar system in Chapter 1. Using a scale on which the Sun was the size of a grapefruit, the nearest star was like another grapefruit a few thousand kilometers away. Because the average distances between stars are so huge compared to the sizes of stars, collisions between stars are extremely rare. However, if we rescale the universe so that our *galaxy* is the size of a grapefruit, the Andromeda Galaxy is like another grapefruit only about 3 meters away, and a few smaller galaxies lie considerably closer. The average distances between galaxies are not much larger than the sizes of galaxies, meaning that collisions between galaxies are inevitable.

Galaxy collisions are spectacular events that unfold over hundreds of millions of years (Figure 15.22). During our short lifetimes, we can see only a snapshot of a collision in progress, distorting the shapes of the colliding galaxies. Collisions must have been even more frequent in the distant past, when the universe was smaller and galaxies were closer together. Observations confirm that distorted-looking galaxies—probably galaxy collisions in progress—were more common in the early universe than they are today.

Computer models show that a collision between two spiral galaxies can form an elliptical galaxy.

We can learn much more about galactic collisions with the aid of computer simulations that allow us to "watch" collisions that in nature take hundreds of millions of years to unfold. These models show that a collision between two spiral galaxies can create an elliptical galaxy (Figure 15.23). Tremendous tidal forces between the colliding galaxies tear apart the two disks, randomizing the orbits of their stars. Meanwhile, a large fraction of their gas sinks to the center of the collision and rapidly forms new stars. Supernovae and stellar winds eventually blow away the rest of the gas. When the cataclysm finally settles down, the merger of the two spirals has produced a single

Figure 15.22

A pair of colliding spiral galaxies known as the Antennae (or NGC 4038/4039). The image taken from the ground (left) reveals their vast tidal tails, while the Hubble Space Telescope image (right) shows the burst of star formation at the center of the collision.

Figure 15.23 MA interactive figure

Several stages in a supercomputer simulation of a collision between two spiral galaxies that results in an elliptical galaxy. At least some of the elliptical galaxies in the present-day universe formed in this way. The whole sequence spans about 1.5 billion years.

elliptical galaxy. Little gas is left for a disk, and the orbits of the stars have random orientations.

Observations support the idea that at least some elliptical galaxies result from collisions and subsequent mergers. Elliptical galaxies dominate the galaxy populations at the cores of dense clusters of galaxies, where collisions should be most frequent. This fact may mean that any spirals once present became ellipticals through collisions.

Stronger evidence comes from structural details of elliptical galaxies, which often attest to a violent past. Some elliptical galaxies have stars and gas clouds with orbits suggesting that they are leftover pieces of galaxies that merged in a past collision. Others are surrounded by shells of stars that may have formed in gas stripped out of a galaxy during a past collision.

Observations show that at least some elliptical galaxies have experienced past collisions.

The most decisive evidence that collisions affect the evolution of elliptical galaxies comes from observations of the **central dominant galaxies** found at the centers of many dense clusters. Central dominant galaxies are giant elliptical galaxies that apparently grew to a huge size by consuming other galaxies through collisions. They frequently contain several tightly bound clumps of stars that probably were the centers of individual galaxies before being swallowed (Figure 15.24). This process of *galactic cannibalism* can create central dominant galaxies more than 10 times as massive as the Milky Way, making them the most massive galaxies in the universe.

Figure 15.24

The central dominant galaxy of the cluster Abell 3827 contains multiple clumps of stars that probably once were the centers of individual galaxies that it consumed. The colors in this image are not real but instead represent levels of brightness, with yellow representing the brightest clumps.

Starbursts We have discussed two general ways in which elliptical galaxies may have formed: (1) as a result of birth in an unusually slow-rotating or high-density protogalactic cloud, and (2) as a result of later collisions and mergers of spiral galaxies. The first scenario makes it easy to account for the lack of hot, young stars and ongoing star formation in elliptical galaxies, since all the cool gas needed for star formation is used up before a spiral disk can form. But how can we account for the lack of young stars and cool gas in ellipticals that formed from more recent collisions?

Computer models suggest that galaxy collisions should ignite huge bursts of rapid star formation—so rapid that all the cool gas would be quickly transformed into stars, leaving little left over to form a disk.

Observational support for this idea comes from a relatively small number of galaxies that appear to be in the midst of such bursts of star formation. We call these objects **starburst galaxies**.

Most galaxies with ongoing star formation appear comfortably settled, steadily forming new stars at modest rates. The Milky Way Galaxy produces an average of about one new star per year. At this rate, the Milky Way won't exhaust the interstellar gas in its disk until long after the Sun has died. Starburst galaxies are not so thrifty. Some form new stars at rates exceeding 100 stars per year, more than 100 times the star formation rate in the Milky Way. These galaxies cannot possibly sustain such a rapid pace of star formation for long. At their current rates of star formation, starburst galaxies would consume *all* their interstellar gas in just a few hundred million years. Because this is a relatively short time compared to the billions of years since galaxies first formed, a starburst must be only a temporary phase in a galaxy's life.

Starburst galaxies are forming stars so quickly that they will run out of star-forming clouds in just a few hundred million years.

Such a high rate of star formation means that there will also be a high incidence of supernovae. The bubbles of hot gas blown out by these many individual supernovae merge into a gigantic bubble so large that it rapidly bursts through any gaseous disk. The hot gas then erupts outward into intergalactic space, creating a **galactic wind** (Figure 15.25).

Many of the most luminous starbursts do indeed appear to be occurring in colliding galaxies. For example, the colliding galaxy pair shown in Figure 15.22 is undergoing a starburst. Starbursts may therefore be the answer to the mystery of why elliptical galaxies lack young stars and cool gas. The starburst uses up most of the cool gas, the galactic wind blows away what remains, and all the hot, massive stars die out within just a few hundred million years after the starburst ends. By the time the collision ends and the merger into an elliptical galaxy is complete, there is simply no cool gas left to support ongoing star formation.

The causes of smaller-scale starbursts are not yet clear. At least some irregular galaxies look irregular because they are currently undergoing collisions and starbursts, but not all irregular galaxies are colliding. For example, the Large Magellanic Cloud is an irregular galaxy that is also undergoing a period of rapid star formation. The starburst leading to this galaxy's irregular appearance might have been triggered by a close encounter with the Milky Way. No matter what their exact causes turn out to be, starbursts clearly represent an important piece in the overall puzzle of galaxy evolution.

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15.4 Quasars and Other Active Galactic Nuclei

Starbursts may be spectacular, but some galaxies display even more incredible phenomena: extreme amounts of radiation, and sometimes powerful jets of material, emanating from deep in their centers (Figure 15.26). These unusually bright galactic centers are usually called **active galactic nuclei**. The most luminous active galactic nuclei are known as **quasars**, which in some cases produce more light than 1000 galaxies the size of the Milky Way.

a This visible light photograph (from the Hubble Space Telescope) shows violently disturbed gas (red) blowing out both above and below the disk.

b This X-ray image from the Chandra X-Ray Observatory shows the same region as the visible-light photograph in (a). The reddish region represents X-ray emission from very hot gas blowing out of the disk. The bright dots in the galactic disk probably represent X-ray emission from accretion disks around black holes or neutron stars produced by recent supernovae.

Figure 15.25 MA interactive photo

Visible-light and X-ray views of a starburst galaxy called M82 and its galactic wind. Both images show the same region, which is about 16,000 light-years across.

Figure 15.26 MA interactive photo

The active galactic nucleus in the elliptical galaxy M87. The bright yellow spot is the active nucleus, and the blue streak is a jet of particles shooting outward from the nucleus at nearly the speed of light.

The glory days of quasars are long past. We find quasars primarily at great distances, telling us that these blazingly luminous objects were most common billions of years ago, when galaxies were in their youth. Because we find no nearby quasars and relatively few nearby galaxies with any type of active galactic nucleus, we conclude that the objects that shine as quasars in young galaxies must become dormant as the galaxies age. Many nearby galaxies that now look quite normal must have centers that once shone brilliantly as quasars.

• What are quasars?

What could possibly be the source of the incredible luminosities of quasars, and why did quasars fade away? A growing body of evidence points to a single answer: The energy output of quasars comes from gigantic accretion disks surrounding **supermassive black holes** with masses millions to billions of times that of our Sun. Before we study how these incredible powerhouses work, let's investigate the evidence that points to their existence.

The Discovery of Quasars In the early 1960s, a young professor at the California Institute of Technology named Maarten Schmidt was busy identifying cosmic sources of radio-wave emission. Radio astronomers would tell him the coordinates of newly discovered radio sources, and he would try to match them with objects seen through visible-light telescopes. Usually the radio sources turned out to be normal-looking galaxies, but one day he discovered a major mystery: A radio source called 3C273 looked like a blue star through a telescope but had strong emission lines at wavelengths that did not appear to correspond to any known chemical element.

Quasars can be more than a trillion times as luminous as the Sun.

After months of puzzlement, Schmidt suddenly realized that the emission lines were not coming from an unfamiliar element at all. Instead, they were emission lines of hydrogen that were hugely redshifted from their normal wavelengths. Schmidt calculated that the expansion of the universe was carrying 3C273 away from us at 17% of the speed of light. He then computed 3C273's distance using Hubble's law, and from its distance and apparent brightness he estimated its luminosity **[Section 11.1]**. What he found was astonishing: 3C273 has a luminosity of about 10^{39} watts, or well over a trillion (10^{12}) times that of our Sun—making it hundreds of times more luminous than the entire Milky Way Galaxy (Figure 15.27). Discoveries of similar but even more distant objects soon followed. Because the first few of these objects were strong sources of radio emission that looked like stars through visible-light telescopes, they were named "quasi-stellar radio sources," or *quasars* for short. Later, astronomers learned that most quasars are not such powerful radio emitters, but the name has stuck.

Most quasars lie more than halfway to the cosmological horizon. The lines in typical quasar spectra are shifted to more than three times their rest wavelengths, which tells us that the light from these quasars emerged when the universe was less than a third of its present age. The light we see from the farthest known quasars began its journey when the universe was less than 1 billion years old.

Evidence from Nearby Active Galactic Nuclei Quasars are difficult to study in detail because they are so far away. Luckily, some quasarlike

objects are much closer to home. About 1% of nearby galaxies have active galactic nuclei that look very much like quasars, except that they are less powerful. (These galaxies are often called *Seyfert galaxies* after astronomer Carl Seyfert, who in 1943 grouped galaxies with active galactic nuclei into a special class.)

The light-emitting regions of active galactic nuclei are so small that even the sharpest images do not resolve them. Our best visible-light images show only that active galactic nuclei must be smaller than 100 light-years across. Radio-wave images made with the aid of *interferometry* **[Section 5.3]** show that these nuclei are even smaller: less than 3 light-years across. Rapid changes in the luminosities of some active galactic nuclei point to an even smaller size.

The immense luminosities of quasars and other active galactic nuclei come from regions no larger than our solar system.

To understand how variations in luminosity tell us about an object's size, imagine that you are a master of the universe and you want to signal one of your fellow masters a billion light-years away. An active galactic nucleus would make an excellent signal beacon, because it is so bright. However, suppose the smallest nucleus you can find is 1 light-year across. Each time you flash it on, the photons from the front end of the source reach your fellow master a full year before the photons from the back end. If you flash it on and off more than once a year, your signal will be smeared out. Similarly, if you find a source that is 1 light-day across, you can transmit signals that flash on and off no more than once a day. If you want to send signals just a few hours apart, you need a source no more than a few light-hours across.

Occasionally, the luminosity of an active galactic nucleus doubles in a matter of hours. The fact that we see a clear signal indicates that the source must be less than a few light-hours across. In other words, *the incredible luminosities of active galactic nuclei and quasars are apparently being generated in a volume of space not much bigger than our solar system.*

Figure 15.27

This Hubble Space Telescope photo shows quasar 3C273, the first object to be identified as a quasar (in 1963). Its luminosity is more than 1 trillion times that of the Sun. (The photo shows a region 275,000 light-years across at the distance of the quasar.)

Radio Galaxies and Jets Another clue to the nature of quasars came in the early 1950s, a decade before their discovery. Radio astronomers noticed that certain galaxies, now called **radio galaxies**, emit unusually strong radio waves. Upon closer inspection, they learned that much of the radio emission comes not from the galaxies themselves but rather from pairs of huge *radio lobes,* one on either side of the galaxy. Today, radio telescopes resolve the structure of radio galaxies in vivid detail (Figure 15.28).

Figure 15.28

This image, made with the Very Large Array in New Mexico, shows radio-wave emission from the radio galaxy Cygnus A. Brighter regions represent stronger radio emission. Notice that the strongest emission comes from two radio lobes that lie far beyond the bounds of the galaxy that we see with visible light (inset photo), but the lobes are clearly connected to the central active galactic nucleus by two long jets of particles.

Figure 15.29

These radio images, taken over a period of several years, show a blob of plasma moving at almost the speed of light in a jet extending from the quasar 3C279; the quasar is at the far left in each image.

At the center of a radio galaxy we see emission from an active galactic nucleus less than a few light-years across. We often see two gigantic **jets** of plasma shooting out of the active galactic nucleus in opposite directions. Using time-lapse radio images taken several years apart, we can track the motions of various plasma blobs in the jets. Some of these blobs move at close to the speed of light. The lobes lie at the ends of the jets, which are sometimes as far as a million light-years from the galactic center.

Active galactic nuclei in radio galaxies can propel huge jets of particles moving at nearly the speed of light.

We now suspect that quasars and radio galaxies are the same types of objects viewed in slightly different ways. We have discovered that many quasars have jets and radio lobes like those seen in radio galaxies (Figure 15.29). Moreover, the active galactic nuclei of many radio galaxies seem to be concealed beneath donut-shaped rings of dark molecular clouds (Figure 15.30). Such structures may look like quasars when they are oriented so that we can see the active galactic nucleus at the center and look like the nuclei of radio galaxies when the ring of dusty gas dims our view of the central object. (A subset of active galactic nuclei called *BL Lac objects* probably represents the centers of radio galaxies whose jets happen to point directly at us.)

Figure 15.30

Artist's conception of the central few hundred light-years of a radio galaxy. The active galactic nucleus, obscured by a ring of dusty molecular clouds, lies at the point from which the jets emerge. If viewed along a direction closer to the jet axis, the active nucleus would not be obscured and would look more like a quasar.

• What is the power source for quasars and other active galactic nuclei?

Astronomers have worked hard to envision physical processes that might explain how radio galaxies, quasars, and other active galactic nuclei release so much energy within such small central volumes. Only one explanation seems to fit: The energy comes from matter falling into a supermassive black hole. The gravitational potential energy of matter falling toward the black hole is converted into kinetic energy, and collisions between infalling particles convert the kinetic energy into thermal energy. The resulting heat causes this matter to emit the intense radiation we observe. As in X-ray binaries, we expect that the infalling matter swirls through an accretion disk before it disappears within the event horizon of the black hole **[Section 13.3]**.

Quasars are probably powered by matter falling into supermassive black holes.

If the supermassive black hole model is correct, it should be able to explain the major observed features of quasars and other active galactic nuclei. In particular, it should explain their extreme luminosities, the fact that they emit radiation over a broad range of wavelengths from radio waves to X rays, and the presence of their powerful jets.

Explaining the extreme luminosities of quasars was the main motivation for the supermassive black hole model. Matter falling into a black hole can generate awesome amounts of energy. During its fall to the event horizon of a black hole, as much as 10–40% of the mass-energy ($E = mc^2$) of a chunk of matter can be converted into thermal energy and ultimately to radiation. Accretion by black holes can therefore produce light far more efficiently than nuclear fusion, which converts less than 1% of mass-energy into photons. Remember that the light is coming not from the black hole itself but rather from the hot gas in the accretion disk.

The environment surrounding a supermassive black hole explains why active galactic nuclei emit light across such a broad wavelength range. Hot gas in and above the accretion disk produces enormous amounts of ultraviolet and X-ray photons. This radiation ionizes surrounding interstellar gas, creating ionization nebulae that emit visible light. (The emission lines produced by these nebulae are the same ones Maarten Schmidt used to measure the first quasar redshifts.) Dust grains in the molecular clouds that encircle the active galactic nucleus (see Figure 15.30) absorb high-energy light and reemit it as infrared light. Finally, the fast-moving electrons that we sometimes see jetting from these nuclei at nearly the speed of light can produce the radio emission from active galactic nuclei.

The powerful jets emerging from active galactic nuclei are more difficult to explain, but certainly there is plenty of energy available for flinging material outward at nearly the speed of light. One plausible model for jet production relies on the twisted magnetic fields thought to accompany accretion disks (Figure 15.31). As an accretion disk spins, it pulls the magnetic field lines that thread it around in circles. Charged particles fly outward along the field lines like beads on a twirling string, forming a jet that shoots out into space.

On the whole, the supermassive black hole model seems to explain the major observed features of quasars and other active galactic nuclei. However, several important mysteries remain unsolved. For example, we do not yet know why quasars eventually run out of gas to accrete

Figure 15.31

This schematic drawing illustrates one model that might explain how supermassive black holes create jets. The model relies on the magnetic field lines thought to thread the accretion disk surrounding a black hole. As the accretion disk spins, it twists the magnetic field lines. Charged particles at the accretion disk's surface can then fly outward along the twisted magnetic field lines.

and stop shining so brightly. We also do not know how those black holes formed in the first place. Nevertheless, the hypothesis that gigantic black holes are responsible for quasars, nearby active galactic nuclei, and radio galaxies is so far withstanding the tests of time and thousands of observations.

• Do supermassive black holes really exist?

The idea that such monster black holes exist has been hard for some astronomers to swallow. Proving that we have found a black hole is tricky. Black holes themselves do not emit any light, so we need to infer their existence from the ways in which they alter their surroundings. In the vicinity of a black hole, matter should be orbiting at high speed around something invisible. We have already examined the evidence for a black hole at the center of our Milky Way **[Section 14.4]**, but what about other galaxies?

Hunting for Supermassive Black Holes Detailed observations of matter orbiting at the centers of nearby galaxies suggest that supermassive black holes are quite common. In fact, it is possible that *all* galaxies might contain supermassive black holes at their centers. One prominent example is the relatively nearby galaxy M87, which features a bright, active galactic nucleus and a jet that emits both radio and visible light (see Figure 15.26). It was already a prime black hole suspect when astronomers pointed the Hubble Space Telescope at its core (Figure 15.32). The spectra they gathered showed blueshifted emission lines on one side of the nucleus and redshifted emission lines

Figure 15.32

This Hubble Space Telescope photo shows gas near the center of the galaxy M87, and the graph shows Doppler shifts of spectra from gas 60 light-years from the center on opposite sides (the circled regions in the photo). The Doppler shifts tell us that gas is orbiting around the galactic center, and precise measurements tell us that orbital speed is about 800 km/s. From the orbital speed and Newton's laws, we find that the central object must have a mass at least 2–3 billion times that of the Sun.

on the other. This pattern of Doppler shifts is the characteristic signature of orbiting gas: On one side of the orbit the gas is coming toward us and hence is blueshifted, while on the other side it is moving away from us and is redshifted. The magnitude of these Doppler shifts shows that the gas, located up to 60 light-years from the center, is orbiting an unseen object at a speed of hundreds of kilometers per second. This high-speed orbital motion indicates that the central object has a mass at least 2–3 billion times that of our Sun.

Observations of rapidly orbiting material at the centers of galaxies indicate that at least some galaxies, and perhaps all of them, harbor supermassive black holes.

Observations of NGC 4258, another galaxy with a visible jet, have delivered even more persuasive evidence. A ring of molecular clouds orbits the nucleus of this galaxy in a circle less than 1 light-year in radius. We can pinpoint these clouds because they amplify the microwave emission lines of water molecules, generating beams of microwaves similar to laser beams. The Doppler shifts of these emission lines allow us to determine the orbits of the clouds very precisely. Their orbital motion tells us that the clouds are circling a single, invisible object with a mass of 36 million solar masses.

As the search for black holes in active galactic nuclei progresses, we are continuing to find examples like these. In each case, a supermassive black hole seems to be the only explanation for the enormous orbital speeds. We may never be 100% certain that these objects are indeed giant black holes. The best we can do is rule out all other possibilities. However, a supermassive black hole is the only thing we know of that could be so massive while remaining unseen.

Black Holes and Galaxy Formation Evidence for supermassive black holes is also found in galaxies whose centers are not currently active. The masses of those black holes follow a very interesting pattern: The mass of the black hole at the center of a galaxy appears to be closely related to the properties of the galaxy's spheroidal component. Detailed studies of the orbital speeds of stars and gas clouds in the centers of nearby galaxies show that the mass of the central black hole is typically about $\frac{1}{500}$ of the mass of the galaxy's bulge (Figure 15.33). Because this relationship holds for galaxies with a wide range of properties, from small spiral galaxies with a bulge mass of less than $10^8 M_{\text{Sun}}$ to giant elliptical galaxies whose spheroidal component exceeds $10^{11} M_{\text{Sun}}$, we conclude that the growth of a central black hole must be closely linked with the process of galaxy formation.

Astronomers have long suspected that galaxy evolution goes hand in hand with the formation of supermassive black holes because quasars were so much more common early in time, when galaxies were growing rapidly. Unfortunately, we do not yet know how that process works. Some scientists have suggested that the black holes formed first out of gas at the center of a protogalactic cloud and that their energy output regulated the growth of the galaxy around them. Other scientists have suggested that clusters of neutron stars resulting from extremely dense starbursts at the centers of young galaxies might have somehow coalesced to form an enormous black hole. For now, the origins of supermassive black holes and their connection to galaxy evolution remain a mystery.

Figure 15.33

The relationship between bulge mass and the mass of a supermassive black hole.

the big picture

Putting Chapter 15 into Perspective

The picture could hardly get any bigger than it has in this chapter. Looking back through both space and time, we have seen a wide variety of galaxies extending nearly to the limits of the observable universe. As you look back, keep sight of these "big picture" ideas:

- The universe is filled with galaxies that come in a variety of shapes and sizes. In order to learn the histories of these galaxies, we must also consider how the universe itself has evolved through time.
- Much of our current understanding of the structure and evolution of the universe is based on measurements of distances to faraway galaxies. These measurements rely on a chain of techniques in which each link in the chain builds upon the links that come before it.
- It has been less than a century since Hubble first proved that the Milky Way is only one of billions of galaxies in the universe. This discovery, and his subsequent discovery of the universe's expansion, provided the foundation upon which modern cosmology has been built. Measurements of the rate of expansion tell us that the universe began about 14 billion years ago.
- Although we do not yet know the complete story of galaxy evolution, we are rapidly learning more. Galaxies probably all began as protogalactic clouds, but they do not always evolve peacefully. Some galaxies collide with neighbors, often with dramatic results.
- The tremendous energy outputs of quasars and other active galactic nuclei, including those of radio galaxies, are probably powered by gas accreting onto supermassive black holes. The centers of many present-day galaxies must still contain the supermassive black holes that once enabled them to shine as quasars.

summary of key concepts

15.1 Islands of Stars

• What are the three major types of galaxies?

(1) **Spiral galaxies** have prominent disks and spiral arms.

(2) **Elliptical galaxies** are rounder and redder than spiral galaxies and contain less cool gas and dust.

(3) **Irregular galaxies** are neither disklike nor rounded in appearance.

• How are galaxies grouped together?

Spiral galaxies tend to collect in groups that contain up to several dozen galaxies. Elliptical galaxies are more common in clusters of galaxies, which contain hundreds to thousands of galaxies, all bound together by gravity.

15.2 Distances of Galaxies

• How do we measure the distances to galaxies?

Our measurements of galaxy distances depend on a chain of methods. The chain begins with **radar ranging** in our own solar system and parallax measurements of distances to nearby stars, then relies on **standard candles** to measure greater distances.

- **What is Hubble's law?**

Hubble's law tells us that more-distant galaxies are moving away faster: $v = H_0 \times d$, where H_0 is **Hubble's constant.** It allows us to determine a galaxy's distance from the speed at which it is moving away from us, which we can measure from its Doppler shift.

- **How do distance measurements tell us the age of the universe?**

Combining distance measurements with velocity measurements tells us Hubble's constant, and the inverse of Hubble's constant tells us how long it would have taken the universe to reach its present size *if* the expansion rate had never changed. Based on Hubble's constant and estimates of how it has changed with time, we now estimate the age of the universe at about 14 billion years, which restricts our view of the universe to objects with **lookback times** smaller than that age.

15.3 Galaxy Evolution

- **How do we observe the life histories of galaxies?**

Today's telescopes enable us to observe galaxies of many different ages because they are powerful enough to detect light from objects with lookback times almost as large as the age of the universe. We can therefore assemble "family albums" of galaxies at different distances and lookback times.

- **How did galaxies form?**

The most successful models of galaxy formation assume that galaxies formed as gravity pulled together regions of the universe that were ever so slightly denser than their surroundings. Gas collected in protogalactic clouds, and stars began to form as the gas cooled.

- **Why do galaxies differ?**

Differences between present-day galaxies probably arise both from conditions in their protogalactic clouds and from collisions with other galaxies. Slowly rotating or high-density protogalactic clouds may form elliptical rather than spiral galaxies. Ellipticals may also form through the merger of spiral galaxies.

15.4 Quasars and Other Active Galactic Nuclei

- **What are quasars?**

Some galaxies have unusually bright centers known as **active galactic nuclei**. A **quasar** is a particularly bright active galactic nucleus. Quasars are generally found at great distances from us, telling us that they were more common early in the history of the universe.

- **What is the power source for quasars and other active galactic nuclei?**

Supermassive black holes are thought to be the power sources for active galactic nuclei. As matter falls into a supermassive black hole through an accretion disk, its gravitational potential energy is transformed with enormous efficiency into thermal energy and then into light.

- **Do supermassive black holes really exist?**

Observations of orbiting stars and gas clouds in the nuclei of galaxies suggest that *all* galaxies may harbor supermassive black holes at their centers. The masses we measure for those black holes are closely related to the properties of the galaxy around them, suggesting that the growth of these black holes is closely tied to the process of galaxy evolution.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 15 Visual Quiz at www.masteringastronomy.com.

The schematic figure above (repeated from Figure 15.17) shows the distance measurement techniques that are best suited to measuring various astronomical distances. Answer the following questions based on the information in the figure.

1. Which distance measurement technique is most suited to measuring objects at a distance of 10 million light-years?
2. Which distance measurement technique is most suited to measuring objects at a distance of 10 light-years?
3. What range of astronomical distances can we currently measure using both parallax and main-sequence fitting?

In the figure above (repeated from Figure 15.28), different colors are used to represent different levels of brightness in radio waves, and the scale bar shows a distance of 100,000 light-years. Use the information in the figure to answer the following questions.

4. What color is used to represent the brightest regions of radio emission?
5. What color is used to represent an absence of detectable radio waves?
6. What is the distance between the two radio hot spots?
7. What is the size of the visible galaxy shown in the inset image?

exercises and problems

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. What are the three major types of galaxies, and how do they look different from one another?
2. Describe the differences between normal spiral galaxies, barred spiral galaxies, and lenticular galaxies.
3. Distinguish between the *disk component* and the *spheroidal component* of a spiral galaxy. Which component includes cool gas and active star formation?
4. What is the major difference between spiral and elliptical galaxies, in terms of the presence or absence of disk and spheroidal components? How does this difference explain the lack of hot, young stars in elliptical galaxies?
5. How are galaxy types in clusters of galaxies different from those in smaller groups and those of isolated galaxies?
6. What do we mean by a *standard candle?* Explain how we can use standard candles to measure distances.
7. Summarize each of the major links in the distance chain. Why are *Cepheid variable stars* so important? Why are white dwarf supernovae so useful, even though they are quite rare?
8. Explain how Hubble used Cepheid variable stars to prove that the Andromeda Galaxy lies beyond the bounds of the Milky Way.
9. What is *Hubble's law?* What is *Hubble's constant?* Explain what we mean when we say that Hubble's constant is between 20 and 24 kilometers per second per million light-years.
10. What is the *Cosmological Principle,* and how is it important to our understanding of the universe?
11. How is the expansion of the surface of an inflating balloon similar to the expansion of the universe? Use the balloon analogy to explain why Hubble's constant is related to the age of the universe.
12. What do we mean by the *lookback time* to a distant galaxy? Briefly explain why lookback times are less ambiguous than distances when discussing objects very far away.
13. What do we mean by a *cosmological redshift?* How does our interpretation of a distant galaxy's redshift differ if we think of it as a cosmological redshift rather than as a Doppler shift?
14. What is the *cosmological horizon,* and what determines how far away it lies?
15. What do we mean by *galaxy evolution?* How do telescopic observations allow us to study galaxy evolution?
16. Briefly describe the starting assumptions for models of galaxy formation and the basic scenario that leads to the formation of a spiral galaxy.
17. Describe two ways in which conditions in a protogalactic cloud might lead to the birth of an elliptical rather than a spiral galaxy. Is there any other general way in which some elliptical galaxies might have formed? Explain.
18. Briefly explain why we expect that collisions between galaxies should be relatively common, while collisions between stars are extremely rare. Why should galaxy collisions have been more common in the past than they are today? What evidence supports the idea that galaxy collisions sometimes occur?
19. What is a *starburst galaxy?* How do observations of starbursts help us understand why the stars in elliptical galaxies are so old?
20. Briefly describe the discovery of *quasars.* Why can we learn more about quasars by studying nearby *active galactic nuclei* and *radio galaxies?*
21. Briefly explain how we can use variations in luminosity to set limits on the size of an object's emitting region. For example, if an object doubles its luminosity in 1 hour, how big can it be?
22. Summarize the supermassive black hole model for the energy output of quasars and other active galactic nuclei. What evidence suggests that such black holes really exist?

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

23. If you want to find a lot of elliptical galaxies, you'll have better luck looking in clusters of galaxies than elsewhere in the universe.
24. Cepheids make good standard candles because they all have exactly the same luminosity.
25. After measuring the galaxy's redshift, I used Hubble's law to estimate its distance.
26. The center of the universe is more crowded with galaxies than any other place in the universe.
27. I'd love to live in one of the galaxies near our cosmological horizon, because then I could see the black void into which the universe is expanding.
28. If someone in a galaxy with a lookback time of $4\frac{1}{2}$ billion years had a superpowerful telescope, they could see our solar system in the process of its formation.
29. Galaxies that are more than 10 billion years old are too far away to see even with our most powerful telescopes.
30. If the Andromeda Galaxy someday collides and merges with the Milky Way, the resulting galaxy may be elliptical.
31. NGC 9645 is a starburst galaxy that has been forming stars at the same furious pace for some 10 billion years.
32. Astronomers proved that quasar 3C473 contains a supermassive black hole when they discovered that its center is dark.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

33. Which of these galaxies is most likely to be oldest? (a) a galaxy in the Local Group (b) a galaxy observed at a distance of 5 billion light-years (c) a galaxy observed at a distance of 10 billion light-years
34. Which of these galaxies would you most likely find at the *center* of a large cluster of galaxies? (a) a large spiral galaxy (b) a giant elliptical galaxy (c) a small irregular galaxy
35. If all the main-sequence stars of a star cluster are typically only one-hundredth as bright as their main-sequence counterparts in the Hyades Cluster, then that cluster's distance from us is (a) 100 times as far as the Hyades' distance. (b) 30 times as far as the Hyades' distance. (c) 10 times as far as the Hyades' distance.
36. Which kind of object is the best standard candle for measuring distances to extremely distant galaxies? (a) a white dwarf (b) a Cepheid variable star (c) a white dwarf supernova
37. Why do virtually all the galaxies in the universe appear to be moving away from our own? (a) because we are located near

where the Big Bang happened (b) because we are located near the center of the universe (c) because expansion causes all galaxies to move away from nearly all others.

38. When we observe a distant galaxy whose photons have traveled for 10 billion years before reaching Earth, we are seeing that galaxy as it was when the universe was about (a) 10 billion years old. (b) 7 billion years old. (c) 4 billion years old.
39. Which of these statements expresses a key assumption in our most successful models for galaxy formation? (a) The distribution of matter was perfectly uniform early in time. (b) Some regions of the universe were slightly denser than others. (c) Galaxies formed around supermassive black holes.
40. The luminosity of a quasar is generated in a region the size of (a) the Milky Way. (b) a star cluster. (c) the solar system.
41. The rate at which supernovae explode in a starburst galaxy that is forming stars 10 times faster than the Milky Way is (a) about the same as in the Milky Way. (b) about 10 times higher than in the Milky Way. (c) about 100 times higher than in the Milky Way.
42. The primary source of a quasar's energy is (a) chemical energy. (b) nuclear energy. (c) gravitational potential energy.

Process of Science

43. *Deviations from Hubble's Law.* Suppose you are measuring distances and velocities of galaxies in order to test Hubble's law. You find that 90% of the galaxies have velocities that are within 200 kilometers per second of the predictions of Hubble's law but 10% have velocities that deviate from the predictions by up to 1000 kilometers per second. Propose a hypothesis that would explain these deviations from Hubble's law, and outline a set of observations that could test your hypothesis.
44. *Why Do Galaxies Differ?* Which explanation for why galaxies differ seems most convincing to you? Explain in two paragraphs why you think that explanation is most convincing, using evidence presented in the chapter to support your position.
45. *Quasar Redshifts.* Some astronomers did not immediately accept that the large redshifts of quasars mean that they must be extremely far away. What properties would an object need in order to have a large redshift but still be no farther than a billion light-years from the Milky Way? How might you be able to test the hypothesis that quasar redshifts are not cosmological in origin?

Group Work Exercise

46. *Counting Galaxies.* In this activity, you will count and classify galaxies in the Hubble Deep Field (Figure 15.1). Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes).
    a. Each team member should individually devise a method for estimating how many galaxies are in the Hubble Deep Field, keeping in mind that almost every object in the image is a galaxy.
    b. Each team member should then apply his or her method to Figure 15.1 and write down the resulting estimate.
    c. Compare your estimates, and explain your estimation methods to each other. The *Scribe* should record each team member's estimate and method.
    d. The *Moderator* should then lead a discussion of the team's results, with the goal of determining why the different methods may have led to different results. The *Scribe* should record the team's proposed explanations.
    e. After the discussion, the *Proposer* should suggest a new estimation method that incorporates the best features of the team members' individual methods, and the *Skeptic* should point out potential problems and suggest improvements to the new method. The team, led by the *Moderator*, should then choose which improvements to make.
    f. The *Scribe* should apply the team's method to Figure 15.1 and record the resulting estimate.

Investigate Further

Short-Answer/Essay Questions

47. *The Hubble Deep Fields.* Both the Hubble Deep Field in Figure 15.1 and the Hubble Ultra Deep Field shown at the beginning of Chapter 1 were chosen for observation in large part because they are completely ordinary parts of the sky. Why do you think astronomers would want to devote so much precious telescope time to observing totally ordinary regions of the sky in such great detail? Explain your reasoning.
48. *Supernovae in Other Galaxies.* In which type of galaxy would you be most likely to observe a massive star supernova, in a giant elliptical galaxy or in a large spiral galaxy? Explain your reasoning.
49. *Hubble's Galaxy Types.* How would you classify the following galaxies using the system illustrated in Figure 15.7? Justify your answers.
    a. Galaxy M101 (Figure 15.2)
    b. Galaxy NGC 4594 (Figure 15.3)
    c. Galaxy NGC 1300 (Figure 15.4)
    d. Galaxy M87 (Figure 15.5)
50. *Cepheids as Standard Candles.* Suppose you are observing Cepheids in a nearby galaxy. You observe one Cepheid with a period of 8 days between peaks in brightness and another with a period of 35 days. Estimate the luminosity of each star. Explain how you arrived at your estimate. (*Hint:* See Figure 15.12.)
51. *Galaxies at Great Distances.* The most distant galaxies that astronomers have observed are much easier to see in infrared light than in visible light. Explain why that is the case.
52. *Universe on a Balloon.* In what ways is the surface of a balloon a good analogy for the universe? In what ways is this analogy limited? Explain why a miniature scientist living in a polka dot on the balloon would observe all other dots to be moving away, with more distant dots moving away faster.
53. *Life Story of a Spiral.* Imagine that you are a spiral galaxy. Describe your life history from birth to the present day. Your story should be detailed and scientifically consistent, but also creative. That is, it should be entertaining while at the same time incorporating current scientific ideas about the formation of spiral galaxies.
54. *Life Story of an Elliptical.* Imagine that you are an elliptical galaxy. Describe your life history from birth to the present. There are several possible scenarios for the formation of elliptical galaxies, so choose one and stick to it. Be creative while also incorporating scientific ideas that demonstrate your understanding.
55. *The Color of an Elliptical Galaxy.* Explain how the color of an old elliptical galaxy has changed during the last 10 billion years. How might you be able to use the galaxy's color to determine when it formed?

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

56. *Counting Galaxies.* Estimate how many galaxies are pictured in Figure 15.1. Explain the method you used to arrive at this estimate. This picture shows about $\frac{1}{30{,}000{,}000}$ of the sky, so multiply your estimate by 30,000,000 to obtain an estimate of how many galaxies like these fill the entire sky.
57. *Distances to Star Clusters.* The distance of the Hyades Cluster is known from parallax to be 151 light-years. Estimate the distance to the Pleiades Cluster using the information in Figure 15.10 and the formula from Cosmic Calculations 15.1.
58. *Cepheids in M100.* Scientists using the Hubble Space Telescope have observed Cepheids in the galaxy M100. Here are the actual data for three Cepheids in M100:
    - Cepheid 1: luminosity = 3.9×10^{30} watts, brightness 9.3×10^{-19} watt/m^2
    - Cepheid 2: luminosity = 1.2×10^{30} watts, brightness 3.8×10^{-19} watt/m^2
    - Cepheid 3: luminosity = 2.5×10^{30} watts, brightness 8.7×10^{-19} watt/m^2

    Compute the distance to M100 with data from each of the three Cepheids. Do all three distance computations agree? Based on your results, estimate the uncertainty in the distance you have found.
59. *Distances from Hubble's Law.* Imagine that you have obtained spectra for several galaxies and have measured the redshift of each galaxy to determine its speed away from us. Here are your results:
    - Galaxy 1: Speed away from us is 15,000 km/s.
    - Galaxy 2: Speed away from us is 20,000 km/s.
    - Galaxy 3: Speed away from us is 25,000 km/s.

    Estimate the distance to each galaxy from Hubble's law. Assume that H_0 = 22 km/s/Mly.
60. *Your Last Hurrah.* Suppose you fell into an accretion disk that swept you into a supermassive black hole. On your way down, the disk radiates 10% of your mass-energy, $E = mc^2$.
    a. What is your mass in kilograms? (Recall that 1 kg = 2.2 pounds.) Calculate how much radiative energy will be produced by the accretion disk as a result of your fall into the black hole.
    b. Calculate approximately how long a 100-watt light bulb would have to burn to radiate this same amount of energy.

Discussion Questions

61. *Cosmology and Philosophy.* One hundred years ago, many scientists believed that the universe was infinite and eternal, with no beginning and no end. When Einstein first developed his general theory of relativity, he found that it predicted that the universe should be either expanding or contracting. He believed so strongly in an eternal and unchanging universe that he modified the theory, a modification he would later call his "greatest blunder." Why do you think Einstein and others assumed that the universe had no beginning? Do you think that a universe with a definite beginning in time, some 14 billion or so years ago, has any important philosophical implications? Explain.
62. *The Case for Supermassive Black Holes.* The evidence for supermassive black holes at the center of galaxies is strong. However, it is very difficult to prove absolutely that they exist because the black holes themselves emit no light. We can only infer their existence from their powerful gravitational influences on surrounding matter. How compelling is the evidence? Do you think astronomers have proved the case for black holes beyond a reasonable doubt? Defend your opinion.

Web Projects

63. *Galaxy Gallery.* Many fine images of galaxies are available on the Web. Collect several images of each major type and build a galaxy gallery of your own. Supply a descriptive paragraph about each galaxy.
64. *Greatest Lookback Time.* Look for recent discoveries of objects with the largest lookback times (or redshifts). What is the most distant known object to date? What kind of object is it?
65. *Future Observatories.* The subject of galaxy evolution is a very active area of research. Look for information on current and future observatories involved in investigating galaxy evolution (such as the James Webb Space Telescope). How big are the planned telescopes? What wavelengths will they look at? When will they be built? Write a short summary of a proposed mission.

16

Dark Matter, Dark Energy, and the Fate of the Universe

learning goals

16.1 Unseen Influences in the Cosmos

- What do we mean by dark matter and dark energy?

16.2 Evidence for Dark Matter

- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?

16.3 Structure Formation

- What is the role of dark matter in galaxy formation?
- What are the largest structures in the universe?

16.4 The Universe's Fate

- Will the universe continue expanding forever?
- Is the expansion of the universe accelerating?

In Chapter 15, we explored the current understanding of how galaxies evolve in an expanding universe. However, we left at least two crucial questions unaddressed: First, what is the source of the gravity that causes galaxies to form and holds them together? Second, what will happen to the expansion of the universe in the future? Both questions are interesting in their own right, but they've taken on even greater importance because our attempts to answer them have led us to two of the greatest mysteries in science.

If we are interpreting the data correctly, then the dominant source of gravity in the universe is an unidentified type of mass, known as *dark matter,* that is completely invisible to our eyes and telescopes. The gravity of dark matter must therefore be the "glue" that holds galaxies like our own together. The fate of the universe itself seems to hinge on the total amount of dark matter and the properties of a mysterious form of energy—often called *dark energy*—that appears to be counteracting the effects of gravity on large scales.

In this chapter, we will explore the evidence for dark matter and dark energy and discuss why their nature remains so mysterious. We'll also investigate how dark matter can produce structures much larger than galaxies and how dark energy may determine the fate of the universe.

essential preparation

1. What determines the strength of gravity? **[Section 4.4]**
2. How does Newton's law of gravity extend Kepler's laws? **[Section 4.4]**
3. How do stars orbit in our galaxy? **[Section14.1]**
4. What is Hubble's law? **[Section 15.2]**

16.1 Unseen Influences in the Cosmos

What is the universe made of? Ask an astronomer this seemingly simple question, and you might see a professional scientist blush with embarrassment. Based on all the available evidence today, the answer to this simple question is "We do not know."

It might seem incredible that we still do not know the composition of most of the universe, and you might wonder why this should be so. After all, we can measure the chemical composition of distant stars and galaxies from their spectra, so we know that stars and gas clouds are made mostly of hydrogen and helium, with small amounts of heavier elements mixed in. But notice the key words "chemical composition." When we say these words, we are talking about the composition of material built from atoms of elements such as hydrogen, helium, carbon, and iron. While it is true that all familiar objects—including people, planets, and stars—are built from atoms, the same may not be true of the universe as a whole.

In fact, we now have good reason to think that the vast majority of the universe is *not* composed of atoms. Instead, the universe may consist largely of a mysterious form of mass known as *dark matter* and a mysterious form of energy known as *dark energy.*

• What do we mean by dark matter and dark energy?

It's easy to talk about dark matter and dark energy, but what do these terms really mean? They are simply names given to unseen influences in the cosmos. In both cases, observations of the universe have led us to

think that something important is out there, even though we cannot identify it, because otherwise the phenomena we have observed do not make sense.

Dark matter is the name given to mass that emits no detectable radiation; we infer its existence from its gravitational effects.

You might at first guess that a galaxy's stars and gas provide all the gravity needed to hold the galaxy together. However, careful observations of how stars and gas clouds move within galaxies have shown that an additional source of gravity is needed: There seems to be far more matter in galaxies than meets the eye. Because this additional matter gives off little or no light, we call it **dark matter**. In other words, *dark matter* is the name we give to whatever unseen influence provides the gravity needed to explain the motions we observe. We've already discussed dark matter briefly in Chapters 1 and 14, noting that studies of the Milky Way's rotation suggest that most of our galaxy's mass is distributed throughout the halo while most of its light comes from stars and gas clouds in the thin galactic disk (see Figure 1.14).

Evidence for the existence of dark energy also comes from careful studies of motion, particularly from studies of the expansion of the universe. From the time that Edwin Hubble first discovered the expansion until just over a decade ago, it was generally assumed that gravity must slow the expansion with time. But now that our telescopes are powerful enough to measure how the expansion rate has changed over time, we are finding that the expansion of the universe is actually accelerating **[Section 16.4]**. Apparently, some mysterious influence is counteracting gravity on very large scales.

Dark energy is the name given to the unseen influence that may be causing the expansion of the universe to accelerate with time.

Dark energy is the most common name given to whatever is causing the expansion to accelerate, but it is not the only name; you may occasionally hear the same unseen influence attributed to *quintessence* or to a *cosmological constant.* The term *dark energy* has become popular because it parallels the term *dark matter,* but there's nothing unusually "dark" about it—after all, we don't expect to see light from the mere presence of a force or energy field. Despite the similarity in their names, dark matter and dark energy are thought to exist for completely different reasons.

Astronomers are generally more comfortable with the notion that dark matter exists than with the notion that dark energy exists. Scientific confidence in dark matter has been building for decades and is now at the point where dark matter seems almost indispensable to explaining the current structure of the universe. That is why we will devote most of this chapter to a discussion of dark matter and its presumed role as the dominant source of gravity in our universe—there is simply a lot more we can say about it. Our discussion of dark energy will wait until the end of the chapter, where we will present the evidence that it also exists and that its nature will determine the fate of the universe.

Before we continue, it's important to think about dark matter and dark energy in the context of science. Strange as these concepts may seem, they have emerged from careful scientific study conducted in accordance with the hallmarks of science discussed in Chapter 3 (see Figure 3.21). Dark matter and dark energy were each proposed to exist because they seemed the simplest way to explain observed motions in the universe. They've each gained credibility because models of the

universe that assume their existence make testable predictions, and, at least so far, observations have borne out some of those predictions. Even if we someday conclude that we were wrong to infer the existence of dark matter or dark energy, we will still need alternative explanations for the observations made to date. One way or the other, what we learn as we explore the mysteries of these unseen influences will forever change our view of the universe.

MA Detecting Dark Matter in a Spiral Galaxy Tutorial, Lessons 1–3

16.2 Evidence for Dark Matter

Let's now examine the evidence for the existence of dark matter and what that evidence indicates about its nature.

• What is the evidence for dark matter in galaxies?

Our review of the evidence for dark matter will start close to home in our own Milky Way Galaxy. Then we'll proceed to other galaxies and clusters of galaxies.

Dark Matter in the Milky Way In Chapter 14, we saw how the Sun's motion around the galaxy reveals the total amount of mass within its orbit. We can use the orbital motion of any other star to measure the mass of the Milky Way within that star's orbit. In principle, we could determine the complete distribution of mass in the Milky Way by doing the same thing with the orbits of stars at every different distance from the galactic center.

In practice, interstellar dust obscures our view of disk stars more than a few thousand light-years away from us, making it very difficult to measure stellar velocities throughout the galaxy. However, radio waves penetrate this dust, and clouds of atomic hydrogen gas emit a spectral line at the radio wave length of 21 centimeters **[Section 14.2]**. Measuring the Doppler shift of this 21-centimeter line tells us a cloud's velocity toward or away from us. With a little geometry, we can then determine the cloud's orbital speed.

We can summarize the results of these orbital measurements with a diagram that plots the orbital speed of objects in a galaxy against their orbital distance. Such a diagram is sometimes called a *rotation curve*. As a simple example, consider how the rotation speed of a merry-go-round depends on the distance from its center. Every object on a merry-go-round goes around the center in the same amount of time (the rotation period of the merry-go-round). But because objects farther from the center move in larger circles, they must move at faster speeds. The speed is proportional to distance from the center, so the plot illustrating the relationship between speed and distance is a steadily rising straight line (Figure 16.1a).

In contrast, orbital speeds in our solar system *decrease* with distance from the Sun (Figure 16.1b). This drop-off in speed with distance occurs because virtually all the mass of the solar system is concentrated in the Sun. The gravitational force holding a planet in its orbit therefore decreases with distance from the Sun, and a smaller force means

a A rotation curve for a merry-go-round.

b The rotation curve for the planets in our solar system.

c The rotation curve for the Milky Way Galaxy. Dots represent stars or gas clouds whose orbital speeds have been measured.

Figure 16.1 MA interactive figure

These graphs show how orbital speeds depend on distance from the center in three different systems.

Figure 16.2

The dark matter associated with a spiral galaxy like the Milky Way occupies a much larger volume than the galaxy's luminous matter. The radius of this dark-matter halo may be 10 times as large as that of the galaxy's halo of stars.

a lower orbital speed. Orbital speeds must drop similarly with distance in any other astronomical system whose mass is concentrated toward the center.

Now let's look at how orbital speed depends on distance in the Milky Way Galaxy. Each individual dot in Figure 16.1c represents the distance from the galactic center and the orbital speed of a particular star or gas cloud. The curve running through the dots represents a best fit to the data. Notice that the orbital speeds remain approximately constant beyond the inner few thousand light-years. This behavior contrasts sharply with the steeply declining orbital speeds in the solar system, leading us to conclude that most ofthe Milky Way's mass must *not* be concentrated at its center. Instead, the orbits of progressively more distant gas clouds must encircle more and more mass. The Sun's orbit encompasses about 100 billion solar masses, but a circle twice as large surrounds twice as much mass, and a larger circle surrounds even more mass.

Orbital speeds in the Milky Way remain high even very far from the center, indicating that a large amount of dark matter lies beyond our galaxy's visible regions.

Orbital speeds in the Milky Way's outer regions therefore imply that most of our galaxy's mass lies well beyond the Sun, tens of thousands of light-years from the galactic center. A more detailed analysis suggests that most of this mass is located in the spherical halo that surrounds the disk of our galaxy and that the total amount of this mass might be *10 times* the total mass of all the stars in the disk. Because we have detected very little radiation coming from this enormous amount of mass, it qualifies as dark matter. If we are interpreting the evidence correctly, the luminous part of the Milky Way's disk is rather like the tip of an iceberg, marking only the center of a much larger clump of mass (Figure 16.2).

Figure 16.3

Measuring the orbital speeds of gas in a spiral galaxy with the 21-centimeter line of atomic hydrogen. Blueshifted lines on the left side of the disk show how fast that gas is moving toward us. Redshifted lines on the right side show how fast that gas is moving away from us.

Dark Matter in Other Galaxies Other galaxies also seem to contain vast quantities of dark matter. We can determine the amount of dark matter in a galaxy by comparing the galaxy's mass to its luminosity. More formally, astronomers calculate the galaxy's *mass-to-light ratio* (see Cosmic Calculations 16.1). First, we use the galaxy's luminosity to estimate the amount of mass that the galaxy contains in the form of stars. Next, we determine the galaxy's total mass by applying the law of gravity to observations of the orbital velocities of stars and gas clouds. If this total mass is larger than the mass that we can attribute to stars, then we infer that the excess mass must be dark matter.

We can measure a galaxy's luminosity as long as we can determine its distance with one of the techniques discussed in Chapter 15 (see Figure 15.17). We simply point a telescope at the galaxy in question, measure its apparent brightness, and calculate its luminosity from its distance using the inverse square law for light **[Section 11.1]**. Measuring the galaxy's total mass requires measuring orbital speeds as far from the galaxy's center as possible, where clouds of atomic hydrogen gas are easier to observe than stars. Most of our observations of galactic rotation therefore come from radio measurements of the 21-centimeter emission line from atomic hydrogen. We use Doppler shifts of that line to determine how fast a cloud is moving toward us or away from us (Figure 16.3).

Plotting the orbital speeds observed at different distances for most spiral galaxies shows that these speeds do not drop off with distance from the center (Figure 16.4). Just as in the Milky Way, this behavior implies that a great deal of matter lies far out in the halos of these galaxies. A detailed analysis tells us that these galaxies also contain at least 10 times as much mass in dark matter as they do in stars. In other words, the composition of typical spiral galaxies is 90% or more dark matter and 10% or less visible matter.

Orbital speeds in the outer regions of other spiral galaxies indicate that they, too, harbor lots of dark matter.

Elliptical galaxies contain very little atomic hydrogen gas and hence do not produce detectable 21-centimeter radiation, so we generally measure masses of elliptical galaxies by observing the motions of their stars. When we compare spectral lines from different regions of an elliptical galaxy, we find that the speeds of the stars remain fairly constant as we look farther from the galaxy's center. Just as in spirals, most of the matter in elliptical galaxies seems to lie beyond the stars we can see and hence must be dark matter. The evidence for dark matter is even more convincing for cases in which we can measure the speeds of globular star clusters orbiting at large distances from the center of an elliptical galaxy. These measurements suggest that elliptical galaxies, like spirals, contain far more matter than we can see.

Figure 16.4

Graphs of orbital speed versus distance for four spiral galaxies. In each galaxy, the orbital speeds remain nearly constant over a wide range of distances from the center, indicating that dark matter is common in spiral galaxies.

• What is the evidence for dark matter in clusters of galaxies?

Observations of galaxy clusters suggest that the ratio of dark matter to luminous matter in clusters is even greater than that in individual galaxies. The evidence for dark matter in clusters comes from three different ways of measuring cluster masses: measuring the speeds of galaxies orbiting the center of the cluster, studying the X-ray emission from hot gas between the cluster's galaxies, and observing how the clusters bend light as *gravitational lenses.*

Orbits of Galaxies in Clusters The idea of dark matter in astronomy is not particularly new. In the 1930s, astronomer Fritz Zwicky was already arguing that clusters of galaxies held enormous amounts of this mysterious stuff (Figure 16.5). Few of his colleagues paid attention, but later observations supported Zwicky's claims.

Zwicky was one of the first astronomers to think of galaxy clusters as huge swarms of galaxies bound together by gravity. It seemed natural to him that galaxies clumped closely in space should all be orbiting one another, just like the stars in a star cluster. He therefore assumed that he could measure cluster masses by observing galaxy motions and applying Newton's laws of motion and gravitation.

Using a spectrograph, Zwicky measured the redshifts of the galaxies in a cluster and used these redshifts to calculate the velocities at which the individual galaxies are moving away from us. He determined the velocity of the cluster as a whole by averaging the velocities of its individual galaxies. He then estimated the orbital speed of a galaxy around the cluster by subtracting this average velocity from the individual galaxy's velocity. Finally, he used these orbital speeds to estimate the cluster's mass and compared this mass to the cluster's luminosity.

cosmic Calculations 16.1

Mass-to-Light Ratio

We define an object's mass-to-light ratio as its total mass in units of *solar masses* divided by its total *visible* luminosity in units of *solar luminosities.* By definition, the mass-to-light ratio of the Sun is

$$\frac{1M_{\text{Sun}}}{1L_{\text{Sun}}} = 1\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

We read this answer with its units as "1 solar mass per solar luminosity."

Example 1: What is the mass-to-light ratio of a $1M_{\text{Sun}}$ red giant with luminosity $100L_{\text{Sun}}$?

Solution: The red giant's mass-to-light ratio is

$$\frac{1M_{\text{Sun}}}{100L_{\text{Sun}}} = 0.01\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

The ratio is *less* than 1 because a red giant puts out *more* light per unit mass than the Sun.

Example 2: The part of the galaxy within the Sun's orbit contains about 100 billion (10^{11}) solar masses of material and has a total luminosity of about 15 billion (1.5×10^{10}) solar luminosities. What is the mass-to-light ratio of the matter within the Sun's orbit?

Solution: We divide the region's mass by its luminosity, both in solar units:

$$\frac{10^{11}M_{\text{Sun}}}{1.5 \times 10^{10}L_{\text{Sun}}} = 6.7\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

The mass-to-light ratio of the matter within the Sun's orbit is about 7 solar masses per solar luminosity. Because this mass-to-light ratio is *greater* than the Sun's ratio of 1 solar mass per solar luminosity, it tells us that most matter in this region is *dimmer* per unit mass than our Sun.

Figure 16.5

Fritz Zwicky, discoverer of dark matter in clusters of galaxies. Zwicky had an eccentric personality, but some of his ideas that seemed strange in the 1930s proved correct many decades later.

To his surprise, Zwicky found that clusters of galaxies have much greater masses than their luminosities would suggest. When he estimated the total mass of stars necessary to account for the overall luminosity of a cluster, he found that it was far less than the mass he measured by studying galaxy speeds. He concluded that most of the matter within these clusters must not be in the form of stars and instead must be almost entirely dark. Many astronomers disregarded Zwicky's result, believing that he must have done something wrong to arrive at such a strange answer. Today, sophisticated measurements of galaxy orbits in clusters confirm Zwicky's original finding.

The orbits of galaxies in clusters tell us that galaxy clusters contain huge amounts of dark matter.

Hot Gas in Clusters A second method for measuring the mass of a galaxy cluster relies on observations of hot gas that fills the space between the galaxies in the cluster (Figure 16.6). This gas (sometimes called the *intracluster medium*) is so hot—typically tens of millions of Kelvin and sometimes above 100 million K—that it emits primarily X rays. It was therefore unknown until the 1960s, when X-ray telescopes were first launched above Earth's atmosphere. Some large clusters have up to seven times as much mass in the form of X-ray-emitting gas as they do in the form of stars.

The hot gas can tell us about dark matter because the temperature of the hot gas depends on the total mass of the cluster. In most clusters, the gas is nearly in a state of *gravitational equilibrium;* that is, its outward pressure balances gravity's inward pull **[Section 10.1]**. In this state of balance, the average kinetic energies of the gas particles are determined primarily by the strength of gravity and hence by the amount of mass within the cluster. Because the temperature of a gas reflects the average kinetic energies of its particles, the gas temperatures we measure with X-ray telescopes tell us the average speeds of the X-ray-emitting particles. We can then use these particle speeds to determine the cluster's total mass.

Temperature measurements of hot gas also tell us the amount of dark matter in clusters, and give results that agree with those we infer from galaxy velocities.

The results obtained with this method agree with the results found by studying the orbital motions of a cluster's galaxies. Even after we

specialTopic | Pioneers of Science

SCIENTISTS ALWAYS TAKE a risk when they publish what they think are ground-breaking results. If their results turn out to be in error, their reputations may suffer. In the case of dark matter, the pioneers in its discovery risked their entire careers. One such pioneer was Fritz Zwicky, who proclaimed the existence of dark matter in clusters of galaxies in the 1930s. Most of his colleagues considered him an eccentric who leapt to premature conclusions.

Another pioneer in the discovery of dark matter was Vera Rubin, an astronomer at the Carnegie Institution. Working in the 1960s, she became the first woman to observe under her own name at California's Palomar Observatory, then the largest telescope in the world. (Another woman, Margaret Burbidge, was permitted to observe at Palomar earlier but was required to apply for time under the name of her husband, also an astronomer.) Rubin first saw the gravitational signature of dark matter in spectra of stars in the Andromeda Galaxy. She noticed that stars in the outskirts of Andromeda moved at surprisingly high speeds, suggesting a stronger gravitational attraction than could be explained by the mass of the galaxy's stars alone. In other words, she found that the rotation curve for Andromeda is relatively flat out to great distances from the center, as we now know is also the case for the Milky Way.

Working with her colleague Kent Ford, Rubin measured the orbital speeds of hydrogen gas clouds in many other spiral galaxies (by studying Doppler shifts in the spectra of hydrogen gas) and discovered that the behavior seen in Andromeda is common. Although Rubin and Ford did not immediately recognize the significance of the results, they soon concluded that the universe must contain substantial quantities of dark matter.

For a while, many astronomers had trouble believing the results. Some astronomers suspected that the bright galaxies studied by Rubin and Ford were unusual. So Rubin and Ford went back to work, obtaining orbital measurements for fainter galaxies. They found similar orbital behavior in these galaxies as well. By the 1980s, the evidence compiled by Rubin, Ford, and others was so overwhelming that even the critics came around. Either the theory of gravity was wrong or the astronomers measuring these orbital speeds had discovered dark matter in spiral galaxies.

account for the mass of the hot gas, we find that the amount of dark matter in a typical galaxy cluster is up to 50 times the combined mass of the stars in the cluster's galaxies. In other words, the gravity of dark matter seems to be binding the galaxies of a cluster together in much the same way that it binds matter within an individual galaxy.

Gravitational Lensing Until recently, astronomers used exclusively methods based on Newton's laws to measure galaxy and cluster masses. These laws keep telling us that the universe holds far more matter than we can see. Can we trust these laws? One way to check is to measure masses in a different way. Today, astronomers have an additional tool for measuring masses: *gravitational lensing.*

Gravitational lensing occurs because masses distort the space around them **[Section 13.3]**. Massive objects can therefore act as **gravitational lenses** that bend light beams passing nearby. This prediction of Einstein's general theory of relativity was first verified in 1919 during an eclipse of the Sun. Because the light-bending angle of a gravitational lens depends on the mass of the object doing the bending, we can measure the masses of objects by observing how strongly they distort light paths.

Gravity's light-bending effects distort the images of galaxies lying behind a cluster, enabling us to measure the cluster's mass without relying on Newton's laws.

Figure 16.7 shows a striking example of how a cluster of galaxies can act as a gravitational lens. Many of the yellow elliptical galaxies concentrated toward the center of the picture belong to the cluster, but at least one of the galaxies pictured does not. The multiple blue ovals are actually all images of the same galaxy. This galaxy lies almost directly behind the center of the cluster, at a much greater distance. We see multiple images of this single galaxy because

Figure 16.6

A distant cluster of galaxies in both visible light and X-ray light. The visible-light photo shows the individual galaxies. The blue-violet overlay represents X-ray emission from extremely hot gas in the cluster, with blue representing the hottest gas and violet representing cooler gas. Evidence for dark matter comes both from the observed motions of the visible galaxies and from the temperature of the hot gas. (The photo shows a region about 8 million light-years across.)

Figure 16.7 MA interactive photo

This Hubble Space Telescope photo shows a galaxy cluster acting as a gravitational lens. The yellow elliptical galaxies are cluster members. The many small blue ovals (such as those indicated by the arrows) are multiple images of a single galaxy that lies almost directly behind the cluster's center. (The picture shows a region about 1.4 million light-years across.)

Figure 16.8 MA interactive figure

A cluster's powerful gravity bends light paths from background galaxies to Earth. If light arrives from several different directions, we see multiple images of the same galaxy.

photons do not follow straight paths as they travel from the galaxy to Earth. Instead, the cluster's gravity bends the photon paths, causing light from the galaxy to arrive at Earth from a few different directions (Figure 16.8). Each alternative path produces a separate, distorted image of the blue galaxy.

Multiple images of a gravitationally lensed galaxy are rare. They occur only when a distant galaxy lies directly behind the lensing cluster. However, single distorted images of gravitationally lensed galaxies are quite common. Figure 16.9 shows a typical example. This picture shows numerous normal-looking galaxies and several arc-shaped galaxies. The oddly curved galaxies are not members of the cluster, nor are they really curved. They are normal galaxies lying far beyond the cluster whose images have been distorted by the cluster's gravity.

Cluster masses measured through gravitational lensing agree with those measured from galaxy velocities and gas temperatures.

Careful analysis of the distorted images created by clusters enables us to measure cluster masses without using Newton's laws. Einstein's theory of general relativity tells us how massive these clusters must be to generate the observed distortions. It is reassuring that cluster masses derived in this way generally agree with those derived from galaxy velocities and X-ray temperatures. The three different methods all indicate that clusters of galaxies hold very substantial amounts of dark matter.

• Does dark matter really exist?

Astronomers have made a strong case for the existence of dark matter, but could they be completely off base? Is it possible that dark matter is a figment of human imagination and that there's a completely different explanation for the observations we've discussed?

All the evidence for dark matter rests on our understanding of gravity. For individual galaxies, the case for dark matter rests primarily on applying Newton's laws of motion and gravity to observations of the orbital speeds of stars and gas clouds. We've used the same laws to make the case for dark matter in clusters, along with additional evidence based on gravitational lensing predicted by Einstein's general theory of relativity. It therefore seems that one of the following must be true:

1. Dark matter really exists, and we are observing the effects of its gravitational attraction.
2. There is something wrong with our understanding of gravity, which is causing us to mistakenly infer the existence of dark matter.

Figure 16.9

Hubble Space Telescope photo of the cluster Abell 2218. The thin, elongated galaxies around the main clump of galaxies on the left side of the picture are the images of background galaxies distorted by the cluster's gravity. By measuring these distortions, astronomers can determine the total amount of mass in the cluster. (The region pictured is about 1.4 million light-years across.)

We cannot yet rule out the second possibility, but most astronomers consider it very unlikely. Newton's laws of motion and gravity are among the most trustworthy tools in science. We have used them time and again to measure masses of celestial objects from their orbital properties. We found the masses of Earth and the Sun by applying Newton's version of Kepler's third law to objects that orbit them **[Section 4.4]**. We used this same law to calculate the masses of stars in binary star systems, revealing the general relationships between the masses of stars and their outward appearances. Newton's laws have also told us the masses of things we can't see directly, such as the masses of orbiting neutron stars in X-ray binaries and of black holes in active galactic nuclei. Einstein's general theory of relativity likewise stands on solid ground, having been repeatedly tested and verified in many observations and experiments. We therefore have good reason to trust our current understanding of gravity.

Either dark matter exists or our current understanding of gravity is incorrect.

In addition, many scientists have made valiant efforts to come up with alternative theories of gravity that could account for the observations without assuming the existence of dark matter. (After all, there's a Nobel Prize waiting for anyone who can substantiate a new theory of gravity.) But no one has yet succeeded in doing so in a way that can also explain the many other observations accounted for by our current theories of gravity.

In essence, our high level of confidence in our current understanding of gravity gives us equally high confidence that dark matter really exists. While we should always keep an open mind about the possibility of future changes in our understanding, we will proceed for now under the assumption that dark matter is real. With that assumption in mind, let's turn our attention to the nature of what seems to be the most common form of matter in the universe.

think about it Should the fact that we have three different ways of measuring cluster masses give us confidence that we really do understand gravity and that dark matter really does exist? Why or why not?

• What might dark matter be made of?

What is all this dark stuff in galaxies and clusters of galaxies? There are two basic possibilities: (1) It could be made of ordinary matter that is built from protons, neutrons, and electrons, but in forms that are too dark for us to detect with current technology; or (2) it could be made of exotic particles that we have yet to discover. Current evidence indicates that while some of the dark matter might be ordinary, most of it must be exotic. To understand this evidence, let's look at the first possibility in more detail.

Ordinary Matter: Not Enough Astronomers consider matter to be "dark" as long as it is too dim for us to see at the great distances of the halo of our galaxy or beyond. Your body is dark matter, because our telescopes could not detect you if you were somehow flung into the halo of our galaxy. Similarly, Earth and other planets are dark matter because we could not see them at great distances either. The "failed stars" known as brown dwarfs **[Section 12.1]** and even faint red main-sequence stars of spectral type M **[Section 11.2]** also qualify as dark matter, because they are too dim for current telescopes to see in the halo.

Figure 16.10

When a dim object such as a small star or brown dwarf passes in front of a more distant star, gravitational lensing temporarily makes the more distant star appear brighter. Searches for such events show that our galaxy's halo does indeed contain dim objects with masses similar to those of small stars, but that these objects do not constitute the majority of the galaxy's dark matter.

However, we have indirect ways of searching for dark matter in the form of planets, brown dwarfs, or dim stars. One technique takes advantage of gravitational lensing. If the halo is full of dark star-like or planet-like objects, then every once in a while, one of them should drift across our line of sight to a more distant star. When this happens, the dark object's gravity can focus more of the distant star's light directly toward Earth, making the star appear much brighter than usual for the several days to weeks it takes the lensing object to pass in front of it (Figure 16.10). Although we do not see the lensing object itself, the duration of the lensing event reveals its mass. Astronomers have detected these types of gravitational lensing events, but the total number they have found is far too small to explain the large amount of dark matter in the halo. In other words, these measurements indicate that there are not enough compact objects made of ordinary matter to account for the bulk of our galaxy's dark matter. Similar measurements rule out the possibility that the dark matter consists of large numbers of black holes formed by the deaths of massive stars.

Searches for gravitational lensing by star-like or planet-like objects in our galaxy's halo show that such objects cannot account for most of the dark matter.

Additional evidence indicating that most of the dark matter cannot be made of familiar particles comes from studies of the early universe. As we will discuss in Chapter 17, models of nuclear fusion in the universe shortly after the Big Bang tell us how the proportions of each isotope of hydrogen, helium, and lithium should depend on the total number of protons and neutrons the universe contains. Measurements of those isotopes in intergalactic space therefore allow us to infer the overall number of protons and neutrons in the observable universe. These measurements show that matter made from protons and neutrons represents only about one-sixth of the total amount of matter in the universe, implying that the other five-sixths is made of something else.

Exotic Matter: The Best Bet These observations have forced astronomers to seriously consider the possibility that most of the matter in the universe is made of unfamiliar particles. Let's begin to explore this possibility by taking another look at a peculiar type of particle that we first encountered in connection with nuclear fusion in the Sun: neutrinos **[Section 10.2]**. Neutrinos are dark by nature because they have no electrical charge and cannot emit electromagnetic radiation of any kind. Moreover, they are never bound together with charged particles in the way that neutrons are bound in atomic nuclei, so their presence cannot be revealed by associated light-emitting particles. Neutrinos interact with other forms of matter through only two of the four forces: gravity and the *weak force*. For this reason, they are said to be *weakly interacting particles*.

The dark matter in galaxies cannot be made of neutrinos, because these very-low-mass particles travel through the universe at enormous speeds and can easily escape a galaxy's gravitational pull. But what if other weakly interacting particles exist that are similar to neutrinos but considerably heavier? They, too, would evade direct detection, but they would move more slowly so their mutual gravity could hold together a large collection of them. Such hypothetical particles are called **weakly interacting massive particles**, or **WIMPs** for short. Note that they are subatomic particles, so the "massive" in their name is relative—they are massive only in comparison to lightweight particles like neutrinos. Such particles could make up most of the mass of a galaxy or cluster of galaxies,

but they would be completely invisible in all wavelengths of light. Most astronomers now consider it likely that WIMPs make up the majority of dark matter, and hence the majority of all matter in the universe.

Scientists suspect that dark matter may consist of weakly interacting particles that are like neutrinos but more massive.

This hypothesis would also explain why dark matter seems to be distributed throughout spiral galaxy halos rather than concentrated in flattened disks like the visible matter. Recall that galaxies are thought to have formed as gravity pulled together matter in regions of slightly enhanced density in the early universe **[Section 15.3]**. This matter would have consisted mostly of dark matter mixed with some ordinary hydrogen and helium gas. The ordinary gas could collapse to form a rotating disk because individual gas particles could lose orbital energy: Collisions among many gas particles can convert some of their orbital energy into radiative energy that escapes from the galaxy in the form of photons. In contrast, WIMPs cannot produce photons, and they rarely interact and exchange energy with other particles. As the gas collapsed to form a disk, WIMPs would therefore have remained stuck in orbits far out in the galactic halo—just where most dark matter seems to be located.

think about it What do you think of the idea that much of the universe is made of as-yet-undiscovered particles? Can you think of other instances in the history of science in which the existence of something was predicted before it was discovered?

Searching for Dark Matter Particles The case for the existence of WIMPs seems fairly strong, but it is still circumstantial. Detecting the particles directly would be much more convincing, and physicists are currently searching for them in two different ways. The first and most direct way is with detectors that can potentially capture WIMPs from space. Because these particles are thought to interact only very weakly, this search requires building large, sensitive detectors deep underground, where they are shielded from other particles from space. These detectors have provided some tantalizing signals, but so far no proof that dark matter particles really exist.

The second way scientists are currently searching for dark matter particles is with particle accelerators—huge machines that smash subatomic particles together at nearly the speed of light. Particle collisions in these accelerators produce a variety of subatomic particles, because much of the energy in each collision is converted into mass according to $E = mc^2$. None of the particles found to date has the characteristics of a WIMP, but scientists are optimistic that the Large Hadron Collider, the most powerful accelerator in the world, will soon reach collision energies great enough to produce the elusive dark matter particles and finally solve this major scientific mystery (Figure 16.11).

Figure 16.11

Aerial photograph of the Large Hadron Collider. The large circle traces the path of the main particle acceleration ring, which lies underground and has a circumference of 27 kilometers.

16.3 Structure Formation

Even without knowing exactly what dark matter is made of, we can still investigate its gravitational effects on the universe. Because galaxies and clusters of galaxies seem to contain much more dark matter than luminous matter, we reason that dark matter's gravitational pull must be the primary force holding these structures together. If that's the case, then the gravitational attraction of dark matter likely pulled galaxies and clusters together in the first place.

• What is the role of dark matter in galaxy formation?

Stars, galaxies, and clusters of galaxies are all *gravitationally bound systems*—their gravity is strong enough to hold them together. In most of the gravitationally bound systems we have discussed so far, gravity has completely overwhelmed the expansion of the universe: While the universe as a whole is expanding, space is *not* expanding within star systems, galaxies, or clusters of galaxies.

Our best guess at how galaxies formed, outlined in Section 15.3, envisions them growing from slight density enhancements that were present in the very early universe. During the first few million years after the Big Bang, the universe expanded everywhere. Gradually, the stronger gravity in regions of enhanced density pulled in matter until these regions stopped expanding and became protogalactic clouds, even as the universe as a whole continued to expand.

The gravity of dark matter was probably the main force that caused protogalactic clouds to become galaxies and galaxies to group into clusters.

Dark matter, if it is indeed the most common form of mass in galaxies, must have provided most of the gravitational attraction responsible for creating protogalactic clouds. The hydrogen and helium gas in the protogalactic clouds collapsed inward and gave birth to stars, while weakly interacting dark matter remained in the outskirts because of its inability to radiate away its orbital energy. According to this model, the luminous matter in each galaxy must still be nestled inside the larger cocoon of dark matter that initiated the galaxy's formation (see Figure 16.2), just as observational evidence seems to suggest.

The formation of galaxy clusters probably echoes the formation of galaxies. Early on, all the galaxies that will eventually constitute a cluster move apart with the expansion of the universe, but the gravity of the dark matter associated with the cluster eventually reverses the trajectories of these galaxies. The galaxies ultimately fall back inward and start orbiting each other randomly, like the stars in the halo of our galaxy.

Some clusters of galaxies apparently have not yet finished forming, because their immense gravity is still drawing in new members. For example, careful studies of galaxy speeds show that the Virgo Cluster of galaxies (about 60 million light-years away) is tugging on the Milky Way and other galaxies of the Local Group. Eventually, this gravitational tug may reverse the motion of the Local Group away from the Virgo Cluster, and our galaxy and its companions will join the cluster.

Similar processes are taking place on the outskirts of other large clusters of galaxies, where we see many galaxies whose speeds indicate that the cluster's gravity is pulling on them and may eventually add them to the cluster. That means many clusters are still attracting galaxies, adding to the hundreds they already contain. On even larger scales, clusters themselves seem to be tugging on one another, indicating that they are parts of even bigger gravitationally bound systems, called **superclusters**, that are still in the early stages of formation (Figure 16.12). But there are structures even larger than superclusters.

Figure 16.12

This diagram represents the motions of galaxies due to effects of gravity. Each arrow represents the amount by which a galaxy's actual velocity (inferred from a combination of observations and modeling) differs from the velocity we'd expect it to have from Hubble's law alone. The Milky Way is at the center of the picture, which shows an area about 600 million light-years across. (Only a representative sample of galaxies is shown.) Notice how the galaxies tend to flow into regions where the density of galaxies is already high. These vast, high-density regions are probably superclusters in the process of formation.

think about it

State whether each of the following is a gravitationally bound system, and explain why: (a) Earth; (b) a hurricane on Earth; (c) the Orion Nebula; (d) a supernova.

• What are the largest structures in the universe?

Beyond about 300 million light-years from Earth, deviations from Hubble's law owing to gravitational tugs are insignificant compared with the universal expansion, so Hubble's law becomes our primary method for measuring galaxy distances **[Section 15.2]**. Using this law, astronomers can make maps of the distribution of galaxies in space. Such maps reveal **large-scale structures** much vaster than galaxy clusters or superclusters.

Mapping Large-Scale Structures Making maps of galaxy locations requires an enormous amount of data. A long-exposure photo showing galaxy positions is not enough, because it does not reveal the galaxy distances. Instead, we must measure the redshift of each individual galaxy so that we can estimate its distance by applying Hubble's law. Current technology allows redshift measurements for hundreds of galaxies during a single night of telescopic observation. As a result, we now have redshift measurements—and hence estimated distances—for hundreds of thousands of galaxies.

Figure 16.13 shows the distribution of galaxies in three slices of the universe, each extending farther out in distance. Our Milky Way Galaxy is located at the vertex at the far left, and each dot represents another galaxy.

Galaxies appear to be arranged in immense structures hundreds of millions of light-years across.

The slice at the left comes from one of the first surveys of large-scale structures, performed in the 1980s. This map, which required years of effort by many astronomers, revealed the complex structure of our region of the universe. It showed that galaxies are not scattered randomly through space but instead are arranged in huge chains and sheets

Figure 16.13

Each of these three wedges shows a "slice" of the universe a few angular degrees in thickness that extends outward from our own Milky Way Galaxy. The dots represent galaxies, shown at their measured distances from Earth. We see that galaxies trace out long chains and sheets surrounded by huge voids containing very few galaxies.

that span many millions of light-years. Clusters of galaxies are located at the intersections of these chains. Between these chains and sheets of galaxies lie giant empty regions called **voids**. The other two slices show data from the more recent Sloan Digital Sky Survey, which measured redshifts for nearly a million galaxies spread across one-fourth of the sky.

Some of the structures in these pictures are amazingly large. For example, the Sloan Great Wall, clearly visible in the center slice, extends more than 1 billion light-years from end to end. Immense structures such as this one apparently have not yet collapsed into randomly orbiting, gravitationally bound systems.

In these surveys, there also appears to be a limit to the size of the largest structures. If you look closely at the right-most slice in Figure 16.13, you'll notice that the overall distribution of galaxies appears nearly uniform on scales larger than about a billion light-years. On such scales, the universe looks much the same everywhere, in agreement with what we expect from the *Cosmological Principle* **[Section 15.2]**.

The Origin of Large Structures Why is gravity collecting matter on such enormous scales? Just as we suspect that galaxies formed from regions of slightly enhanced density in the early universe, we suspect that these larger structures were also regions of enhanced density. Galaxies, clusters, superclusters, and the Sloan Great Wall probably all started as higher-density regions of different sizes. The voids in the distribution of galaxies probably started as lower-density regions.

The structure we see in today's universe probably mirrors the distribution of dark matter when the universe was very young.

If this model of structure formation is correct, then the structures we see in today's universe should mirror the original distribution of dark matter very early in time. Supercomputer models of structure formation can now simulate the growth of galaxies, clusters, and larger structures from tiny density enhancements as the universe evolves (Figure 16.14). The results of these models look remarkably similar to the slices of the universe in Figure 16.13, bolstering our confidence in this scenario. However, the models do not tell us *why* the universe started with these slight density enhancements—that is a topic for the next chapter. Nevertheless, it seems increasingly clear that these "lumps" in the early universe were the seeds of all the marvelous structures we see in the universe today.

Figure 16.14 MA interactive figure

Frames from a supercomputer simulation of structure formation. These five boxes depict the development of a cubical region that is now 140 million light-years across. The labels above the boxes give the age of the universe and the labels below give the size of the box as it expands with time. Notice that the distribution of matter is only slightly lumpy when the universe is young (left frame). Structures grow more pronounced with time as the densest lumps draw in more and more matter.

Fate of the Universe Tutorial, Lessons 1–3

16.4 The Universe's Fate

We now arrive at one of the ultimate questions in astronomy: How will the universe end? Edwin Hubble's work established that galaxies are rapidly flying away from one another [Section 15.2], but the gravitational pull of each galaxy on every other galaxy acts to slow the expansion. The possible outcomes seem to fall into two general categories. If gravity is strong enough, the expansion will someday halt and the universe will begin collapsing, eventually ending in a cataclysmic crunch. Alternatively, if the expansion can overcome the pull of gravity, the universe will continue to expand forever, growing ever colder as its galaxies grow ever farther apart. The fate of the universe thus seems to boil down to a simple question: Is the universe expanding fast enough to escape its own gravitational pull and keep on expanding forever?

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

Fire and Ice, by Robert Frost

• Will the universe continue expanding forever?

Just over a decade ago, astronomers thought they could answer this question simply by measuring the amount of matter in the universe. The greater the matter density, the greater the overall strength of gravity and the higher the likelihood that gravity will someday halt the expansion. Precise calculations show that if there were no other forces acting on the universe, gravity could eventually win out over the current expansion if the present-day matter density of the universe exceeded a seemingly minuscule 10^{-29} gram per cubic centimeter—roughly equivalent to a few hydrogen atoms in a volume the size of a closet. This density of matter, called the **critical density**, marks the dividing line between eternal expansion and eventual collapse for a universe in which gravity is the only force affecting the expansion rate.

The universe does not appear to contain enough dark matter to prevent it from expanding forever.

Observations indicate that the total amount of matter, including dark matter, falls short of this critical density. Adding up the luminosities of galaxies shows that all the mass contained in stars amounts to only about 0.5% of the critical density. That means the overall matter density could exceed the critical density only if dark matter contributes about 200 times as much mass as the luminous matter. However, our observations of galaxy clusters indicate that they contain about 50 times as much matter in the form of dark matter as in stars, or only about a quarter of the amount of dark matter needed to halt the expansion.

For the actual matter density to exceed the critical density, even more dark matter would have to lie beyond the boundaries of clusters. But evidence indicates that it does not. If large-scale structures contained a higher proportion of dark matter than clusters, the influence of that extra dark matter would show up in the velocities of galaxies near those large-scale structures: Larger amounts of dark matter would cause greater deviations from Hubble's law. We have not observed such deviations, so we conclude that the total density of matter in the universe falls short of the critical density. The universe therefore seems destined to keep expanding forever, even in the absence of a mysterious force capable of opposing gravity and causing the expansion to accelerate.

• Is the expansion of the universe accelerating?

Observations of distant white dwarf supernovae have recently enabled us to study the expansion of the universe in an entirely new way. Because white dwarf supernovae are standard candles that can be seen even when they occur in the most distant galaxies **[Section 15.2]**, we can use them to measure how the expansion of the universe has changed over long periods of time. Those measurements show that gravity is not slowing the expansion down at all. Instead, the expansion of the universe appears to be speeding up, suggesting that some mysterious repulsive force—possibly produced by *dark energy*—is pushing all the universe's galaxies apart.

This discovery has far-reaching implications for both the fate of the universe and our understanding of the forces that govern its behavior on large scales. To understand the evidence for an accelerating expansion, we must become more familiar with the possible futures of the universe.

Four Expansion Patterns Astronomers subdivide the two general possibilities for the fate of the universe, expanding forever or someday collapsing, into four broad categories. Each represents a particular pattern of change in the future expansion rate (Figure 16.15). We will call these four possible expansion patterns *recollapsing, critical, coasting,* and *accelerating.* The first three possibilities assume that gravity is the only force that affects the expansion rate of the universe, while the fourth adds a repulsive force (from dark energy) that opposes the gravity of matter.

The expansion rate of the universe depends on the balance between gravity, which acts to slow the expansion, and dark energy, which acts to accelerate it.

- **A recollapsing universe:** If there is no dark energy and the matter density of the universe is *larger* than the critical density, the collective gravity of matter will eventually halt the universe's expansion and reverse it. All matter will come crashing back together, and the

Figure 16.15

Four models for the fate of the universe. Each diagram shows how the size of a circular slice of the universe changes with time in a particular model. The slices are the same size at the present time, marked by the red line, but the models make different predictions about the sizes of the slices in the past and future. The first three cases assume that there is no dark energy, so that the fate of the universe depends only on how its actual density compares to the critical density. The last case assumes that a repulsive force—perhaps from dark energy—is accelerating the expansion with time. (The diagram assumes continuous acceleration, but observations suggest that the expansion of our universe actually slowed down for a few billion years before acceleration began.)

entire universe will end in a fiery "Big Crunch." We call this a recollapsing universe because the final state, with all the matter collapsed together, would look much like the state in which the universe began. (A recollapsing universe is sometimes called a *closed universe*, because mathematical calculations show that it must have an overall geometry that closes in upon itself like the surface of a sphere, but in more dimensions **[Section 17.3]**.)

- **A critical universe:** If there is no dark energy and the matter density of the universe *equals* the critical density, the collective gravity of matter is exactly the amount needed to balance the expansion. The universe will never collapse but will expand more and more slowly as time progresses. We call this a critical universe because its density is the critical density. (Mathematically speaking, a critical universe's overall geometry is "flat"—like the surface of a table but in more dimensions. A critical universe is therefore one example of what astronomers call a *flat universe*.)
- **A coasting universe:** If there is no dark energy and the matter density of the universe is *smaller* than the critical density, the collective gravity of matter cannot halt the expansion. The universe will keep expanding (coasting) forever, with little change in its rate of expansion. (A coasting universe is sometimes called an *open universe*, because its overall geometry is more like the open surface of a saddle than like the closed surface of a sphere.)
- **An accelerating universe:** If dark energy exerts a repulsive force that causes the expansion of the universe to *accelerate* with time, then the expansion rate will grow with time. Galaxies will recede from one another with increasing speed, and the universe will become cold and dark more quickly than would a coasting universe. (Depending on the strength of gravity relative to the repulsive force, the overall geometry of an accelerating universe could be flat, open, or closed. As we'll discuss in Chapter 17, current evidence suggests a flat geometry.)

think about it Do you think that one of the potential fates of the universe is preferable to the others? If so, why? If not, why not?

specialTopic | What Did Einstein Consider His Greatest Blunder?

SHORTLY AFTER EINSTEIN completed his general theory of relativity in 1915, he found that it predicted that the universe could not be standing still: The mutual gravitational attraction of all the matter would make the universe collapse. Because Einstein thought at the time that the universe should be eternal and static, he decided to alter his equations. In essence, he inserted a "fudge factor" called the *cosmological constant* that acted as a repulsive force to counteract the attractive force of gravity.

Had he not been so convinced that the universe should be standing still, Einstein might instead have come up with the correct explanation for why the universe is not collapsing: because it is still expanding from the Big Bang. After Hubble discovered the universal expansion, Einstein allegedly called his invention of the cosmological constant "the greatest blunder" of his career.

However, astronomers have begun to take the idea of a cosmological constant more seriously. In the mid-1990s, a few observations suggested that the oldest stars were slightly older than the age of the universe derived from Hubble's constant under the assumption that gravity is the only force affecting the universe's expansion. Clearly, stars cannot be older than the universe. If these observations were being interpreted correctly, the universe had to be older than the age implied by Hubble's constant. If the expansion rate has accelerated, so that the universe is expanding faster today than it was in the past, then the age of the universe would be greater than the age people were inferring from Hubble's constant (see Figure 16.16). What could cause the expansion of the universe to accelerate over time? The repulsive force represented by a cosmological constant,of course.

Further study of these confusing observations eventually showed that the oldest stars probably are *not* older than the age of the universe derived from Hubble's constant. However, measurements of distances to high-redshift galaxies using white dwarf supernovae as standard candles now show that the expansion *is* accelerating. The measured acceleration is just what one would expect from a cosmological constant arising from dark energy. Einstein's greatest blunder, it seems, might not have been such a blunder after all.

Figure 16.16

Data from white dwarf supernovae are shown along with four possible models for the expansion of the universe. Each curve shows how the average distance between galaxies changes with time for a particular model. A rising curve means that the universe is expanding, and a falling curve means that the universe is contracting. Notice that the supernova data fit the accelerating universe better than the other models.

Evidence for Acceleration Figure 16.16 illustrates how the average distance between galaxies should change with time for each possibility. The lines for the accelerating, coasting, and critical universes always continue upward as time increases, because in these cases the universe is always expanding. The steeper the slope, the faster the expansion. In the recollapsing case, the line begins on an upward slope but eventually turns around and declines as the universe contracts. All the lines pass through the same point and have the same slope at the moment labeled "now," because the current separation between galaxies and the current expansion rate in each case must agree with observations of the present-day universe.

The age that we infer for the universe from its expansion rate differs in each case. A recollapsing universe requires the least amount of time to arrive at the current separation between galaxies—the example in Figure 16.16 goes from zero separation to the current separation in less than 5 billion years. The cases for which gravity is less important require more time to achieve the current separation between galaxies. The ages we infer from the examples in Figure 16.16 are 8.8 billion years for a critical universe, 13 billion years for a coasting universe, and around 14 billion years for an accelerating universe.

see it for yourself Toss a ball in the air, and observe how it rises and falls. Then make a graph to illustrate your observations, with time on the horizontal axis and height on the vertical axis. Which universe model does your graph most resemble? What is the reason for that resemblance? How would your graph look different if Earth's gravity were not as strong?

This relationship between the age of the universe and its expansion pattern enables us to determine the expansion pattern from observations of white dwarf supernovae. Because these supernovae are so bright and make such excellent standard candles, we can measure their distances and redshifts even when they are more than halfway across the observable universe. The distance we measure essentially tells us the lookback time to

Distances measured to faraway white dwarf supernovae indicate that the expansion of the universe is speeding up.

the supernova, while its redshift tells us how much the universe has expanded since the time of the supernova explosion.

Combining these two pieces of information for supernova explosions at different times in the past tells us how the expansion rate has changed with time. Supernova data gathered during the last decade, plotted as dots in Figure 16.16, fit the curve for an accelerating universe better than any of the other models. In other words, observational evidence supports an accelerating universe.

Exactly why the expansion of the universe might be accelerating remains a deep mystery. No known force could push the universe's galaxies apart, and an enormous amount of energy would be required to do so. Of course, our lack of understanding does not stop us from giving a name to whatever is causing the acceleration, and we have already discussed why it is often called *dark energy.* Keep in mind, however, that we do not yet have any idea of what dark energy might actually be. However, if our interpretation of the observations is correct, dark energy is the most prevalent form of energy in the universe, outstripping the total mass-energy of all the matter in the universe—including dark matter.

A Never-Ending Expansion? Whether or not dark energy exists, and whatever dark energy might turn out to be, it now seems likely that the universe is indeed doomed to expand forever, its galaxies receding ever more quickly into an icy, empty future. After all, our examination of the strength of gravity showed it to be too weak to stop the expansion even without dark energy, and the acceleration due to dark energy would only seem to seal this fate. Some scientists even hypothesize that the dark energy could eventually cause galaxies, stars, and planets to break apart and disperse.

Based on current data, the universe seems destined to expand forever.

However, before we convince ourselves that we now know the fate of the universe, we should bear in mind that forever is a very long time. The universe may hold other surprises that we haven't yet discovered, surprises that might force us to rethink what might happen between now and the end of time.

This is the way the world ends
This is the way the world ends
This is the way the world ends
Not with a bang but a whimper.

From *The Hollow Men*, by T. S. Eliot

the big picture

Putting Chapter 16 into Perspective

We have found that there may be much more to the universe than meets the eye. Dark matter too dim for us to see seems to far outweigh the stars, and a mysterious dark energy may be even more prevalent (see Figure 16.17 for a review). Here are some key "big picture" ideas to remember from this chapter:

- Dark matter and dark energy sound very similar, but they are each hypothesized to explain different observations. *Dark matter* is thought to exist because we detect its gravitational influence. *Dark energy* is a term given to the source of the force that may be accelerating the expansion of the universe.
- Either dark matter exists or we do not understand how gravity operates on large scales. There are many reasons to be confident in our understanding of gravity, so most astronomers conclude that dark matter is real.
- Dark matter seems by far to be the most abundant form of mass in the universe. We still do not know what it is, but we suspect it is largely made up of some type of as-yet-undiscovered subatomic particles.

(*continued*)

Figure 16.17. Dark Matter and Dark Energy

Scientists suspect that most of the matter in the universe is *dark matter* we cannot see, and that the expansion of the universe is accelerating because of a *dark energy* we cannot directly detect. Both dark matter and dark energy have been proposed to exist because they bring our models of the universe into better agreement with observations, in accordance with the process of science. This figure presents some of the evidence supporting the existence of dark matter and dark energy.

1 **Dark Matter in Galaxies:** Applying Newton's laws of gravity and motion to the orbital speeds of stars and gas clouds suggests that galaxies contain much more matter than we observe in the form of stars and glowing gas.

Orbital speeds of stars and gas clouds remain high even quite far from our galaxy's center . . .

. . . indicating that the visible portion of our galaxy lies at the center of a much larger volume of dark matter.

HALLMARK OF SCIENCE **A scientific model must seek explanations for observed phenomena that rely solely on natural causes.** Orbital motions within galaxies demand a natural explanation, which is why scientists proposed the existence of dark matter.

2 **Dark Matter in Clusters:** Further evidence for dark matter comes from studying galaxy clusters. Observations of galaxy motions, hot gas, and gravitational lensing all suggest that galaxy clusters contain far more matter than we can directly observe in the form of stars and gas.

This cluster of galaxies acts as a gravitational lens *to bend light from a single galaxy behind it into the multiple blue shapes in this photo. The amount of bending allows astronomers to calculate the total amount of matter in the cluster.*

HALLMARK OF SCIENCE **Science progresses through creation and testing of models of nature that explain the observations as simply as possible.** Dark matter accounts for our observations of galaxy clusters more simply than alternative hypotheses.

3 **Structure Formation:** If dark matter really is the dominant source of gravity in the universe, then its gravitational force must have been what assembled galaxies and galaxy clusters in the first place. We can test this prediction using supercomputers to model the formation of large-scale structures both with and without dark matter. Models with dark matter provide a better match to what we observe in the real universe.

Supercomputer models in which dark matter is the dominant source of gravity show galaxies organized into strings and sheets similar in size and shape to those we observe in the real universe.

4 **Universal Expansion and Dark Energy:** The expansion of a universe consisting primarily of dark matter would slow down over time (due to gravity), but observations suggest that the expansion is actually speeding up. Scientists hypothesize that a mysterious *dark energy* is causing the expansion to accelerate. Models that include both dark matter and dark energy agree more closely with observations than models containing dark matter alone.

HALLMARK OF SCIENCE **A scientific model makes testable predictions about natural phenomena. If predictions do not agree with observations, the model must be revised or abandoned.** Observations of the universe's expansion have forced us to further modify our models of the universe to include dark energy along with dark matter.

- If dark matter is the dominant source of gravity in the universe, then it is the glue that binds together galaxies, clusters, superclusters, and other large-scale structures in the universe. All this structure has probably grown from regions where the density of dark matter in the early universe was slightly enhanced.
- The fate of the universe depends on whether gravity can halt the expansion. The total strength of gravity seems too weak to do so even when we account for dark matter, and the evidence that the expansion is accelerating because of dark energy only reinforces the suggestion that the expansion will never cease.

summary of key concepts

16.1 Unseen Influences in the Cosmos

• What do we mean by dark matter and dark energy?

Dark matter and **dark energy** have never been directly observed, but each has been proposed to exist because it seems the simplest way to explain a set of observed motions in the universe. *Dark matter* is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds. *Dark energy* is the name given to whatever may be causing the expansion of the universe to accelerate.

16.2 Evidence for Dark Matter

• What is the evidence for dark matter in galaxies?

The orbital velocities of stars and gas clouds in galaxies do not change much with distance from the center of the galaxy. Applying Newton's laws of gravitation and motion to these orbits leads to the conclusion that the total mass of a galaxy is far larger than the mass of its stars. Because no detectable visible light is coming from this matter, we call it *dark matter*.

• What is the evidence for dark matter in clusters of galaxies?

We have three different ways of measuring the amount of dark matter in clusters of galaxies: from galaxy orbits, from the temperature of the hot gas in clusters, and from the **gravitational lensing** predicted by Einstein. All of these methods agree, indicating that the total mass of a cluster is about 50 times the mass of its stars, implying huge amounts of dark matter.

• Does dark matter really exist?

We infer that dark matter exists from its gravitational influence on the matter we can see, leaving two possibilities: Either dark matter exists or there is something wrong with our understanding of gravity. We cannot rule out the latter possibility, but we have good reason to be confident that our current understanding of gravity is correct and dark matter is real.

• What might dark matter be made of?

There does not appear to be enough ordinary matter in the form of stars, planets, and gas clouds to account for all the dark matter. Therefore, scientists suspect that most of it is made of exotic particles known as **WIMPs** that have yet to be directly detected.

16.3 Structure Formation

• What is the role of dark matter in galaxy formation?

Because most of a galaxy's mass is in the form of dark matter, the gravity of that dark matter is probably what formed protogalactic clouds and galaxies from slight density enhancements in the early universe.

• What are the largest structures in the universe?

Galaxies appear to be distributed in gigantic chains and sheets that surround great voids. These giant structures trace their origin directly back to regions of slightly enhanced density early in time.

16.4 The Universe's Fate

• Will the universe continue expanding forever?

Even before we consider the possibility of dark energy, the evidence points to eternal expansion. The **critical density** is the average matter density the universe would need for the strength of gravity to eventually halt the expansion. The overall matter density of the universe appears to be only about 25% of the critical density.

• Is the expansion of the universe accelerating?

Observations of distant supernovae indicate that the expansion of the universe is speeding up. No one knows the nature of the mysterious force due to dark energy that could be causing this acceleration.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 16 Visual Quiz at www.masteringastronomy.com.

This schematic figure shows a more complicated expansion history than the four idealized models shown in Figure 16.15. Answer the questions using the information given in this figure.

1. At Time A, is the expansion of the universe accelerating, coasting, or decelerating?
2. At Time B, is the expansion of the universe accelerating, coasting, or decelerating?
3. At Time C, is the expansion of the universe accelerating, coasting, or decelerating?
4. At Time D, is the expansion of the universe accelerating, coasting, or decelerating?

exercises and problems

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Define *dark matter* and *dark energy,* and clearly distinguish between them. What types of observations have led scientists to propose the existence of each of these unseen influences?
2. Describe how orbital speeds in the Milky Way depend on distance from its center, and explain how those orbital speeds indicate the presence of large amounts of dark matter.
3. How do orbital speeds depend on distance from the center in other spiral galaxies? What do they tell us about the galaxy masses and dark matter?
4. How do we measure the masses of elliptical galaxies? What do these masses lead us to conclude about dark matter in elliptical galaxies?
5. Briefly describe the three different ways of measuring the mass of a cluster of galaxies. Do the results from the different methods agree? What do they tell us about dark matter in galaxy clusters?
6. What is *gravitational lensing?* Why does it occur? How can we use it to estimate the masses of lensing objects?
7. Briefly explain why the conclusion that dark matter exists rests on assuming that we understand gravity correctly. Is it possible that our understanding of gravity is not correct? Explain.
8. In what sense is dark matter "dark"? Briefly explain why objects like you, planets, and even dim stars could qualify as dark matter.
9. Explain how we search for dim star-like (or planet-like) objects in the halo of our galaxy. Why can't the dark matter consist of objects like these?
10. Explain what we mean when we say that a neutrino is a *weakly interacting particle.* Why can't the dark matter in galaxies be made of neutrinos?
11. What are *WIMPs?* Why does it seem possible that dark matter consists of these particles, even though we do not yet know what they are?
12. Briefly explain why dark matter is thought to have played a major role in the formation of galaxies and larger structures in the universe. What evidence suggests that large structures are still forming?
13. What does the large-scale structure of the universe look like? Explain why we think this structure reflects the density patterns of the early universe.
14. What do we mean by the *critical density* of the universe? According to current evidence, how does the actual density of matter in the universe compare to the critical density?
15. Describe and compare four possible patterns to the expansion of the universe: recollapsing, critical, coasting, and accelerating. Observationally, how can we decide which of the four possible expansion models is the right one? Based on the current evidence, which model is favored?

16. Assuming the acceleration is real, what does it imply for the fate of the universe? What does current evidence suggest for the fate if the acceleration is not real? Explain.

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

17. Strange as it may sound, the majority of mass and energy in the universe may take forms that we are unable to detect directly.
18. A cluster of galaxies is held together by the mutual gravitational attraction of all the stars in the cluster's galaxies.
19. We can estimate the total mass of a cluster of galaxies by studying the distorted images of galaxies whose light passes through the cluster.
20. Clusters of galaxies are the largest structures that we have so far detected in the universe.
21. The primary evidence for an accelerating universe comes from observations of young stars in the Milky Way.
22. There is no doubt remaining among astronomers that the fate of the universe is to expand forever.
23. Dark matter is called "dark" because it blocks light from traveling between the stars.
24. If the universe has more dark matter than we think, then it is also younger than we think.
25. The distance to a white dwarf supernova with a particular redshift is larger in an accelerating universe than in a universe with no acceleration.
26. If dark matter consists of WIMPs, then we should be able to observe photons produced by collisions between these particles.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Dark matter is inferred to exist because (a) we see lots of dark patches in the sky. (b) it explains how the expansion of the universe can be accelerating. (c) we can observe its gravitational influence on visible matter.
28. Dark energy has been hypothesized to exist in order to explain (a) observations suggesting that the expansion of the universe is accelerating. (b) the high orbital speeds of stars far from the center of our galaxy.(c) the giant voids between large-scale structures in the universe.
29. Measurements of the Milky Way's rotation tell us that stars in the outskirts of the galaxy (a) orbit the galactic center just as fast as stars closer to the center. (b) rotate rapidly on their axes. (c) have orbital periods similar to those of stars closer to the center.
30. Strong evidence for the existence of dark matter comes from observations of (a) our solar system. (b) the center of the Milky Way. (c) clusters of galaxies.
31. A photograph of a cluster of galaxies shows distorted images of galaxies that lie behind it at greater distances. This is an example of what astronomers call (a) dark energy. (b)spiral density waves. (c) a gravitational lens.
32. Based on the observational evidence, is it possible that dark matter doesn't really exist? (a) No, there is too much evidence to think that it could be in error. (b) Yes, but only if there is something wrong with our current understanding of how gravity should work on large scales. (c) Yes, but only if all the observations themselves are in error.
33. Based on current evidence, which of the following is considered a likely candidate for the majority of the dark matter in galaxies? (a) subatomic particles that we have not yet detected (b) swarms of dim, red stars (c) super massive black holes
34. Which region of the early universe was most likely to become a galaxy? (a) a region whose matter density was lower than average (b) a region whose matter density was higher than average (c) a region with a high concentration of dark energy
35. The major evidence for the idea that the expansion of the universe is accelerating comes from observations of (a) white dwarf supernovae. (b) the orbital speeds of stars within galaxies. (c) the evolution of quasars.
36. Which of these possible types of universe would *not* expand forever? (a) a critical universe (b) an accelerating universe (c) a recollapsing universe

Process of Science

37. *Dark Matter.* Overall, how convincing do you find the case for the existence of dark matter? Write a short essay in which you first describe what we mean by dark matter and what evidence there is for its existence and then give your opinion about the strength of the evidence.
38. *Dark Energy.* Overall, how convincing do you find the case for the existence of dark energy? Write a short essay in which you first describe what we mean by dark energy and what evidence there is for its existence and then give your opinion about the strength of the evidence.
39. *Alternative Gravity.* Suppose someone proposes a new theory of gravity that claims to explain observed motion in galaxies and clusters of galaxies without dark matter. Briefly describe at least one other test that you would expect the new theory to be able to pass if it is, in fact, a better theory of gravity than general relativity.

Group Work Exercise

40. *Dark Matter and Distorted Galaxies.* In this exercise, you will learn about how dark matter in galaxy clusters distorts images of background galaxies through gravitational lensing. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes).
    a. Study the gravitational lensing diagram in Figure 16.8 and notice how gravitational lensing causes the image of a background galaxy to shift to a position *farther* from the center of the cluster. The *Proposer* should explain how this shift affects the lensed image of a galaxy and predict how the lensed image of a spherical galaxy would look. The *Skeptic* should then decide whether she or he agrees with the *Proposer's* reasoning and, if not, should offer an alternative prediction.
    b. On a large piece of paper, the *Scribe* should draw a diagram like the one that follows, using a straight edge to make sure the lines are straight. They should all intersect at the same place and the circle should be close to the point of intersection. (Note that the point at which the lines intersect represents the center of a galaxy cluster, and the circle represents the true position and shape of a spherical galaxy at a much greater distance from Earth.)

c. The *Moderator* should then determine the effect of the cluster's lensing shift on the galaxy's image as follows. For each dot on the circle, draw another dot farther to the right along the same line, so that the distance between the two dots is equal to the length of the line labeled "lensing shift." Then connect the new dots to see the shape of the lensed image. Does it agree with the *Proposer's* prediction? Was the *Skeptic's* prediction better? How does it compare with the lensed galaxy images in Figure 16.9? Discuss the possible reasons for any discrepancies you find.

Investigate Further

Short-Answer/Essay Questions

41. *The Future Universe.* Based on current evidence concerning the growth of structure in the universe, briefly describe what you would expect the universe to look like on large scales about 10 billion years from now.
42. *Dark Matter and Life.* State and explain at least two reasons why dark matter is (or was) essential for life to exist on Earth.
43. *Orbital Speed vs. Radius.* Draw a graph showing how orbital speeds depend on radius for each of the following hypothetical galaxies. Make sure the radius axis has approximate distances labeled.
    a. All the mass of the galaxy is concentrated in the center.
    b. The galaxy has a constant mass density inside 20,000 light-years and zero density outside of this region.
    c. The galaxy has a constant mass density inside 20,000 light-years, and its enclosed mass increases proportionally to the distance outside of this region.
44. *Dark Energy and Supernova Brightness.* When astronomers began measuring the brightnesses and redshifts of distant white dwarf supernovae, they expected to find that expansion of the universe was slowing down. Instead they found that it was speeding up! Were the distant supernovae brighter or fainter than expected? Explain why. (*Hint:* In Figure 16.16, the position of a supernova point on the vertical axis is proportional to its redshift. Its position on the horizontal axis is proportional to its brightness—supernovae seen farther back in time are not as bright as those seen closer in time.)
45. *What Is Dark Matter?* Describe at least three possible constituents of dark matter. Explain how we would expect each to interact with light, and how we might go about detecting its existence.
46. *Alternative Gravity.* How would gravity have to be different in order to explain the orbital speeds observed in galaxies without the need for dark matter? Would gravity need to be stronger or weaker than expected at very large distances? Explain.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

47. *White Dwarf M/L.* What is the mass-to-light ratio of a $1M_{\text{Sun}}$ white dwarf with luminosity $0.001L_{\text{Sun}}$?
48. *Supergiant M/L.* What is the mass-to-light ratio of a $30M_{\text{Sun}}$ supergiant star with luminosity $300{,}000L_{\text{Sun}}$?
49. *Solar System M/L.* What is the mass-to-light ratio of the solar system?
50. *Mass from Orbital Velocities.* Study the graph of orbital speeds for the spiral galaxy NGC 7541, which is shown in Figure 16.4.
    a. Use the orbital velocity law from Cosmic Calculations 14.1 to determine the mass (in solar masses) of NGC 7541 enclosed within a radius of 30,000 light-years from its center. (*Hint:* 1 light-year = 9.461×10^{15} m.)
    b. Use the orbital velocity law to determine the mass of NGC 7541 enclosed within a radius of 60,000 light-years from its center.
    c. Based on your answers to parts (a) and (b), what can you conclude about the distribution of mass in this galaxy?
51. *Weighing a Cluster.* A cluster of galaxies has a radius of about 6.7 million light-years (6.2×10^{22} m) and its hot gas has a temperature of 8×10^7 K, corresponding to an orbital speed for the galaxies of 1080 km/s. Estimate the mass of the cluster using the orbital velocity law from Cosmic Calculations 14.1. Give your answer in both kilograms and solar masses. Suppose the combined luminosity of all the stars in the cluster is $8 \times 10^{12}L_{\text{Sun}}$. What is the cluster's mass-to-light ratio?

Discussion Questions

52. *Dark Matter or Revised Gravity.* One possible explanation for the evidence we find for dark matter is that we are currently using the wrong law of gravity to measure the masses of very large objects. If we really do misunderstand gravity, then many fundamental theories of physics, including Einstein's theory of general relativity, will need to be revised. Which explanation for our observations do you find more appealing: dark matter or revised gravity? Explain why. Why do you suppose most astronomers find dark matter more appealing?
53. *Our Fate.* Scientists, philosophers, and poets alike have speculated on the fate of the universe. How would you prefer the universe as we know it to end, in a "Big Crunch" or through eternal expansion? Explain the reasons behind your preference.

Web Projects

54. *Gravitational Lenses.* Gravitational lensing occurs in numerous astronomical situations. Compile a catalog of 5–10 examples from the Web, including pictures of lensed stars, quasars, and galaxies. Give a one-paragraph explanation of what's happening in each picture.
55. *Accelerating Universe.* Search for the most recent information about the possible acceleration of the expansion of the universe. Write a one- to three-page report on your findings.
56. *The Nature of Dark Matter.* Use the Web to find recent reports on the possible nature of dark matter. Write a one- to three-page report that summarizes the latest ideas about what dark matter is made of.

17

The Beginning of Time

learning goals

17.1 The Big Bang

- What were conditions like in the early universe?
- What is the history of the universe according to the Big Bang theory?

17.2 Evidence for the Big Bang

- How do we observe the radiation left over from the Big Bang?
- How do the abundances of elements support the Big Bang theory?

17.3 The Big Bang and Inflation

- What aspects of the universe were originally unexplained by the Big Bang model?
- How does inflation explain these features of the universe?
- How can we test the idea of inflation?

17.4 Observing the Big Bang for Yourself

- Why is the darkness of the night sky evidence for the Big Bang?

The universe has been expanding for about 14 billion years. During that time, matter collected into galaxies. Stars formed in those galaxies, producing heavy elements that were recycled into later generations of stars. One of these late-coming stars formed about $4\frac{1}{2}$ billion years ago, in the outskirts of a galaxy called the Milky Way. This star was born with a host of planets that formed in a flattened disk surrounding it. One of these planets became covered with life that evolved into ever more complex forms. Today, the most advanced life-form on this planet, human beings, can look back on this series of events and marvel at how the universe created conditions suitable for life.

Up to this point in the book, we have discussed how the matter produced in the early universe gradually assembled into planets, stars, and galaxies. However, we have not yet addressed one big question: Where did *matter itself* come from? To answer this question, we must go far beyond the most distant galaxies. We must go back not only to the origins of matter and energy but to the beginning of time itself.

MA Hubble's Law Tutorial, Lessons 1–3

17.1 The Big Bang

Is it really possible to study the origin of the entire universe? Not long ago, questions about the origin of everything we see were considered unfit for scientific study. That attitude began to change with Hubble's discovery that the universe is expanding. This discovery led to the insight that all things very likely sprang into being at a single moment in time, in an event that we have come to call the *Big Bang*. Today, powerful telescopes allow us to view how galaxies have changed over time, and at great distances we see young galaxies still in the process of forming [Section 15.3]. These observations confirm that the universe is gradually aging, just as we should expect if the entire universe really was born some 14 billion years ago.

Unfortunately, we cannot see back to the very beginning of time. Light from the most distant galaxies shows us what the universe looked like when it was about 1 billion years old. Beyond these galaxies, we have not yet found any objects shining brightly enough for us to see them. Ultimately, we face an even more fundamental problem. The universe is filled with a faint glow of radiation that appears to be leftover energy from the Big Bang. This faint glow is light that has traveled freely through space since the universe was about 380,000 years old, which is when the universe first became transparent to light. Before that time, light could not pass freely through the universe, so there is no possibility of seeing light from earlier times. Just as we must rely on mathematical modeling to determine what the Sun is like on the inside, we must also use modeling to investigate what the universe was like during its earliest moments.

essential preparation

1. How can we know what the universe was like in the past? [Section 1.1]
2. Where do objects get their energy? [Section 4.3]
3. What is matter? [Section 5.1]
4. How does light tell us the temperatures of planets and stars? [Section 5.2]

Figure 17.1

The universe cools as it expands. We can calculate past temperatures by using the laws of physics and the current temperature of the universe (about 3 K). This graph shows the results. Notice that both axis scales use powers of 10. (The graph extends to the present: 14 billion years $\approx 4 \times 10^{17}$ seconds.)

Figure 17.2

Electron–antielectron creation and annihilation. Reactions like these constantly converted photons to particles and vice versa in the early universe.

• What were conditions like in the early universe?

Scientific models of the conditions that prevailed in the early universe are based on fundamental principles of physics. The universe is cooling and becoming less dense as it expands, so it must have been hotter and denser in the past. Calculating exactly how hot and dense the universe must have been when it was more compressed is similar to calculating the temperature and density of gas in a balloon when you squeeze it, except that the conditions become much more extreme. Figure 17.1 shows the results of such calculations.

Particle Creation and Annihilation The universe was so hot during its first few seconds that photons could transform themselves into matter, and vice versa, in accordance with Einstein's formula $E = mc^2$ **[Section 4.3]**. Reactions that create and destroy matter are now relatively rare in the universe, but physicists can reproduce such reactions in laboratories, such as the Large Hadron Collider (see Figure 16.11).

One such reaction is the creation or destruction of an *electron–antielectron pair* (Figure 17.2). When two photons collide with a total energy greater than twice the mass-energy of an electron (the electron's mass times c^2), they can create two brand-new particles: a negatively charged electron and its positively charged twin, the *antielectron* (also known as a *positron*). The electron is a particle of **matter**, and the antielectron is a particle of **antimatter**. The reaction that creates an electron–antielectron pair also runs in reverse. When an electron and an antielectron meet, they *annihilate* each other, transforming all their mass-energy back into photon energy.

The very early universe was so hot that energy could be transformed into matter and vice versa.

Similar reactions can produce or destroy any particle–antiparticle pair, such as a proton and antiproton or a neutron and antineutron. The early universe therefore was filled with an extremely hot and dense blend of photons, matter, and antimatter, converting furiously back and forth. Despite all these vigorous reactions, describing conditions in the early universe is straightforward, at least in principle. We simply need to use the laws of physics to calculate the proportions of the various forms of radiation and matter at each moment in the universe's early history. The only difficulty is our incomplete understanding of the laws of physics.

To date, physicists have investigated the behavior of matter and energy at temperatures as high as those that existed in the universe just *one ten-billionth* (10^{-10}) of a second after the Big Bang, giving us confidence that we actually understand what was happening at that early time. Our understanding of physics is less certain under the more extreme conditions that prevailed even earlier, but we have some ideas about what the universe was like when it was a mere 10^{-38} second old, and perhaps a glimmer of what it was like at the age of just 10^{-43} second. These tiny fractions of a second are so small that, for all practical purposes, we are studying the very moment of creation—the Big Bang itself.

Fundamental Forces To understand the changes that occurred in the early universe, it helps to think in terms of *forces*. Everything that happens in the universe today is governed by four distinct forces: *gravity*, *electromagnetism*, the *strong force*, and the *weak force*. We have already encountered each of these forces individually.

Gravity is the most familiar of the four forces, acting as the "glue" that holds planets, stars, and galaxies together. The electromagnetic force, which depends on the electrical charge of a particle instead of its mass, is far stronger than gravity. It is therefore the dominant force between particles in atoms and molecules, responsible for all chemical and biological reactions. However, the existence of both positive and negative electrical charge causes the electromagnetic force to lose out to gravity on large scales, even though both forces decline with distance following an inverse square law. Most astronomical objects are electrically neutral overall, making the electromagnetic force unimportant on that scale. Gravity therefore becomes the dominant force for such objects, because more mass always means more gravity.

The strong and weak forces operate only over extremely short distances, making them important within atomic nuclei but not on larger scales. The strong force binds atomic nuclei together **[Section 10.2]**. The weak force plays a crucial role in nuclear reactions such as fission and fusion, and it is the only force besides gravity that affects weakly interacting particles such as neutrinos and WIMPs (weakly interacting massive particles **[Section 16.2]**).

Although the four forces behave quite differently from one another, scientists now think that they are actually just different aspects of a smaller number of more fundamental forces (Figure 17.3). At the high temperatures that prevailed in the early universe, the four forces were not as distinct as they are today.

As an analogy, think about ice, liquid water, and water vapor. These three substances are quite different from one another in appearance and behavior, yet they are just different phases of the single substance H_2O. In a similar way, experiments have shown that the electromagnetic and weak forces lose their separate identities under conditions of very high temperature or energy and merge together into a single **electroweak force**. At even higher temperatures and energies, the electroweak force may merge with the strong force and ultimately with gravity. Theories that predict the merger of the electroweak and strong forces are called **grand unified theories**, or **GUTs** for short. The merger of the strong, weak, and electromagnetic forces is therefore often called the *GUT force*. Many physicists suspect that at even higher energies, the GUT force and gravity merge into a single "super force" that governs the behavior of everything. (Among the names you may hear for theories linking all four forces are *supersymmetry*, *superstrings*, and *supergravity*.)

The four forces that operate in the universe today may have been unified early in time and later became distinct as the universe expanded and cooled.

If these ideas are correct, then the universe was governed solely by the "super force" in the first instant after the Big Bang. As the universe expanded and cooled, the super force split into gravity and the GUT force, which then split further into the strong and electroweak forces. Finally, the electroweak force split into the electromagnetic and weak forces, making all four forces distinct. As we'll see shortly, these changes in the fundamental forces probably occurred before the universe was one ten-billionth of a second old.

Figure 17.3

The four forces are distinct at low temperatures but may merge at very high temperatures, such as those that prevailed during the first fraction of a second after the Big Bang.

• What is the history of the universe according to the Big Bang theory?

The **Big Bang theory**—the scientific theory of the universe's earliest moments—is based on applying known and tested laws of physics to the idea that everything we see today, from Earth to the cosmic horizon, began

Figure 17.4 MA interactive figure

A time line for the eras of the early universe. The only era not shown is the era of galaxies, which began with the birth of stars and galaxies when the universe was a few hundred million years old.

as an incredibly tiny, hot, and dense collection of matter and radiation. The Big Bang theory describes how expansion and cooling of this unimaginably intense mixture of particles and photons could have led to the present universe of stars and galaxies, and it explains several aspects of today's universe with impressive accuracy. We will discuss the evidence supporting the Big Bang theory later in this chapter. First, in order to help you understand the significance of the evidence, we'll examine the history of the universe according to this theory.

To make sense of the universe's early history, we will divide it into a series of *eras*, or time periods, each distinguished from the next by some major change in physical conditions as the universe cools. As you can see in Figure 17.1, the temperature dropped extremely rapidly during the first second after the Big Bang: While the temperature was above 10^{32} K during the first instant of time, it had already dropped below 10^{10} K by the time the universe was just 1 second old. Because the behavior of matter and energy depends on temperature, this enormous drop in temperature led to dramatic changes in the universe.

Many of the key events that shaped today's universe occurred within the first few minutes after the Big Bang.

The rest of this section describes the conditions and transitions that marked the eras of the early universe. You'll find it useful to refer to the time line shown in Figure 17.4 as you read along. Notice that most of the key events in the history of the universe occurred in a very short period of time. It will take you longer to read this chapter than it took the universe to progress through the first five eras we will discuss.

The Planck Era As we work our way back through time, we reach the limit of our current scientific ability to understand the physical conditions when the universe was an incomprehensibly young 10^{-43} second old and the temperature was above 10^{32} K. This instant in time is called the *Planck time* after physicist Max Planck, one of the founders of the science of quantum mechanics. We refer to all times prior to the Planck time (the first 10^{-43} second) as the **Planck era**.

We do not yet understand the physics of the universe well enough to describe what it was like during the Planck era.

Current theories of physics cannot adequately describe the extreme conditions that must have existed during the Planck era. According to the laws of quantum mechanics, there must have been substantial energy fluctuations from point to point in the very early universe. Because energy and mass are equivalent, Einstein's general theory of relativity tells us that these energy fluctuations must have generated a rapidly changing gravitational field that randomly warped space and time. During the Planck era, these random energy fluctuations should have been so large that our current theories cannot describe what might have been happening. The problem is that we do not yet have a theory that links quantum mechanics (our successful theory of the very small) and general relativity (our successful theory of the very big). Perhaps someday we will be able to merge these theories of the very small and the very big into a single "theory of everything." Until that happens, science cannot describe the universe of the Planck era.

Nevertheless, while we can't say much about the Planck era itself, we have some idea of how it ended and what followed. If you look back at Figure 17.3, you'll see that all four forces are thought to merge into the single, unified "super force" at temperatures above 10^{32} K. In that case, the Planck era would have been a time of ultimate simplicity, when just a single force operated in nature. The Planck era came to an end at

the instant when the temperature dropped below 10^{32} K, allowing gravity to become distinct from the other three forces, which were still merged as the GUT force. By analogy to ice crystals forming as a liquid cools, we say that gravity "froze out" at the end of the Planck era.

The GUT Era The universe subsequently entered the **GUT era**, when two forces operated in the universe: gravity and the GUT force. Recall that the GUT force is a unified force representing the merger of the strong, weak, and electromagnetic forces. According to grand unified theories, these three forces merge together only at temperatures above 10^{29} K (see Figure 17.3). The GUT era therefore lasted only until the temperature fell to 10^{29} K, at which point the GUT force split into the strong and electroweak forces. The universe reached this temperature at an age of a mere 10^{-38} second, which means the entire GUT era lasted less than a trillion-trillion-trillionth of a second.

Energy released near the end of the GUT era may have caused a dramatic expansion of the universe known as inflation.

Our current understanding of physics allows us to say only slightly more about the GUT era than the Planck era, and none of our ideas about the GUT era have been sufficiently well-tested to give us great confidence about what occurred during that time. However, if the grand unified theories are correct, the freezing out of the strong and electroweak forces at the end of the GUT era may have released an enormous amount of energy, causing a sudden and dramatic expansion of the universe that we call **inflation**. In a mere 10^{-36} second, pieces of the universe the size of an atomic nucleus may have grown to the size of our solar system. Inflation sounds bizarre, but as we will discuss later, it can explain several important features of today's universe.

The Electroweak Era Once the GUT force split at the end of the GUT era, the universe entered an era during which three distinct forces operated: gravity, the strong force, and the electroweak force. We call this time the **electroweak era**, because the electromagnetic and weak forces were still unified in the electroweak force. Intense radiation filled all of space, as it had since the Planck era, spontaneously producing matter and antimatter particles that almost immediately annihilated each other and turned back into photons.

The universe continued to expand and cool throughout the electroweak era, dropping to a temperature of 10^{15} K when it reached an age of 10^{-10} second. This temperature is still 100 million times hotter than the temperature in the core of the Sun, but it was low enough for the electromagnetic and weak forces to freeze out from the electroweak force. After this instant (10^{-10} second), all four forces were forever distinct in the universe.

The end of the electroweak era marks an important transition not only in the physical universe, but also in human understanding of the universe. The theory that unified the weak and electromagnetic forces, developed in the 1970s, predicted the emergence of new types of particles (called the W and Z bosons, or *weak bosons*) at temperatures above the 10^{15} K that pervaded the universe when it was 10^{-10} second old. In 1983, experiments performed in a huge particle accelerator near the French/Swiss border reached energies equivalent to such high temperatures for the first time. The new particles showed up just as predicted, produced from the extremely high energy in accord with $E = mc^2$.

In other words, we have direct experimental evidence concerning the conditions in the universe at the end of the electroweak era. We do *not* have any direct experimental evidence of conditions prior to that time. Our theories concerning the earlier parts of the electroweak era and the GUT era consequently are much more speculative than our theories describing the universe from the end of the electroweak era to the present.

Experimental evidence supports the current theory about the universe since it was 10^{-10} second old, at the end of the electroweak era, but we have no direct evidence about earlier times.

The Particle Era As long as the universe was hot enough for the spontaneous creation and annihilation of particles, the total number of particles was roughly in balance with the total number of photons. Once it became too cool for this spontaneous exchange of matter and energy to continue, photons became the dominant form of energy in the universe. We refer to the time between the end of the electroweak era and the moment when spontaneous particle production ceased as the **particle era**, to emphasize the role of subatomic particles during this period.

During the first part of the particle era, photons continued (as they had done in earlier eras) to turn into all sorts of exotic particles that we no longer find freely existing in the universe today, including *quarks*—the building blocks of protons and neutrons. By the end of the particle era, all quarks had combined into protons and neutrons, which shared the universe with other particles such as electrons, neutrinos, and perhaps WIMPs. The particle era came to an end when the universe reached an age of 1 millisecond (0.001 second) and the temperature had fallen to 10^{12} K. At this point, it was no longer hot enough to produce protons and antiprotons (or neutrons and antineutrons) spontaneously from pure energy.

Protons must have slightly outnumbered antiprotons during the particle era, or we would not be here today.

If the universe had contained equal numbers of protons and antiprotons (or neutrons and antineutrons) at the end of the particle era, all of the pairs would have annihilated each other, creating photons and leaving essentially no matter in the universe. From the obvious fact that the universe contains matter, we conclude that protons must have slightly outnumbered antiprotons at the end of the particle era.

We can estimate the size of the imbalance between matter and antimatter by comparing the present numbers of protons and photons in the universe. The two numbers should have been similar in the very early universe, but today photons outnumber protons by about a billion to one. We conclude that for every billion antiprotons in the early universe, there were about a billion and one protons. As a result, for each 1 billion protons and antiprotons that annihilated each other at the end of the particle era, a single proton was left over. This slight excess of matter over antimatter makes up all the ordinary matter in the present-day universe.

The Era of Nucleosynthesis So far, everything we have discussed occurred within the first 0.001 second of the universe's existence—a time span shorter than the time it takes you to blink an eye. At this point, the protons and neutrons left over after the annihilation of antimatter began to fuse into heavier nuclei. However, the heat of the universe remained so high that most nuclei broke apart as fast as they formed. This dance of fusion and breakup marked the **era of nucleosynthesis**.

The era of nucleosynthesis ended when the universe was about 5 minutes old. After this time, the density in the expanding universe had dropped so much that fusion no longer occurred, even though the temperature was still about a billion Kelvin (10^9 K)—much hotter than the temperature at the center of the Sun today. When fusion ceased, about 75% of the mass of the ordinary matter in the universe remained as individual protons, or hydrogen nuclei. The other 25% of this mass had fused into helium nuclei, with trace amounts of deuterium (hydrogen with a neutron) and lithium (the next heaviest element after hydrogen and helium). Except for the relatively small amount of matter that stars later forged into heavier elements, the chemical composition of the universe remains the same today.

Most of the helium in the universe was made during the first 5 minutes.

The Era of Nuclei At the end of the era of nucleosynthesis, the universe consisted of a very hot plasma of hydrogen nuclei, helium nuclei, and electrons. This basic picture held for the next 380,000 years as the universe continued to expand and cool. The fully ionized nuclei moved independently of electrons during this period (rather than being bound with electrons in neutral atoms), which we call the **era of nuclei**. Throughout this era, photons bounced rapidly from one electron to the next, just as they do deep inside the Sun today **[Section 10.2]**, never managing to travel far between collisions. Any time a nucleus captured an electron to form a complete atom, one of the photons quickly ionized it.

Photons began to travel freely through the universe about 380,000 years after the Big Bang, when electrons first combined with nuclei to make atoms.

The era of nuclei ended when the universe was about 380,000 years old and the temperature had fallen to about 3000 K—roughly half the temperature of the Sun's surface today. Hydrogen and helium nuclei captured electrons for good, forming stable, neutral atoms for the first time. With electrons bound into atoms, the universe became transparent, as if a thick fog had lifted. Photons, formerly trapped among the electrons, began to stream freely across the universe. We still see these photons today as the *cosmic microwave background*, which we will discuss shortly.

The Era of Atoms and the Era of Galaxies We've already discussed the rest of the story in earlier chapters. The end of the era of nuclei marked the beginning of the **era of atoms**, when the universe consisted of a mixture of neutral atoms and plasma (ions and electrons), along with a large number of photons. Thanks to the slight density enhancements present in the universe at this time and the gravitational attraction of dark matter, the atoms and plasma slowly assembled into protogalactic clouds. Stars formed in these clouds, transforming the gas clouds into galaxies. The first galaxies had formed by the time the universe was about 1 billion years old, beginning what we call the **era of galaxies**.

The first galaxies formed by the time the universe was a billion years old.

The era of galaxies continues to this day. Generation after generation of star formation in galaxies steadily produces elements heavier than helium and incorporates them into new star systems. Some of these star systems develop planets, and on at least one of these planets, life burst into being a few billion years ago. Now here we are, thinking about it all.

Early Universe Summary Figure 17.5 (on pages 478–479) summarizes the major ideas from our brief overview of the history of the universe

Figure 17.5. The Early Universe

The Big Bang theory is a scientific model that explains how the present-day universe developed from an extremely hot and dense beginning. This schematic diagram shows how conditions in the early universe changed as the universe expanded and cooled with time.

3 Temperatures shortly after the Big Bang were so hot that photons could change into elementary particles and vice versa. The early universe was therefore filled with photons and all kinds of elementary particles.

4 After an age of 0.001 second, the universe became too cool to produce protons and antiprotons from pure energy. These particles then annihilated, leaving only a small fraction of the original protons left over.

5 Up until 5 minutes after the Big Bang, the universe was still hot enough to fuse hydrogen into helium. The observed amount of helium in the universe agrees with predictions of the Big Bang theory.

6 Photons bounced around among the free electrons in the universe until an age of 380,000 years, when the electrons were captured by atoms. Then the photons began to move freely through the universe, and we observe them today as the cosmic microwave background.

10^{-10} second

0.001 second

5 minutes

380,000 years

Particle Era

Era of Nucleosynthesis

Era of Nuclei

Era of Atoms

10^{15} K

10^{12} K

10^{9} K

3000 K

7 Galaxies began to form by the time the universe was about a billion years old. See the Cosmic Context on pages 498–499 for an overview of galaxy evolution.

cooler

as it is described by the Big Bang theory. In the rest of this chapter, we will discuss the evidence that supports this theory. Before you read on, be sure you spend a few minutes studying Figure 17.5.

17.2 Evidence for the Big Bang

Like any scientific theory, the Big Bang theory is a model of nature designed to explain a set of observations. If it is close to the truth, it should be able to make predictions about the real universe that we can verify through more observations or experiments. The Big Bang model has gained wide scientific acceptance for two key reasons:

- It predicts that the radiation that began to stream across the universe at the end of the era of nuclei should still be present today. Sure enough, we find that the universe is filled with what we call the **cosmic microwave background**. Its characteristics precisely match what we expect according to the Big Bang model.
- It predicts that some of the original hydrogen in the universe should have fused into helium during the era of nucleosynthesis. Observations of the actual helium content of the universe closely match the amount of helium predicted by the Big Bang model.

Let's take a closer look at this evidence, starting with the cosmic microwave background.

• How do we observe the radiation left over from the Big Bang?

The first major piece of evidence supporting the Big Bang theory was announced in 1965. Arno Penzias and Robert Wilson, two physicists working at Bell Laboratories in New Jersey, were calibrating a sensitive microwave antenna designed for satellite communications (Figure 17.6). (*Microwaves* fall within the radio portion of the electromagnetic spectrum; see Figure 5.2.) Much to their chagrin, they kept finding unexpected "noise" in every measurement they made with the antenna. The noise was the same no matter where they pointed their antenna, indicating that it came from all directions in the sky and ruling out the possibility that it came from any particular astronomical object or from any place on Earth.

Meanwhile, physicists at nearby Princeton University were busy calculating the expected characteristics of the radiation left over from the heat of the Big Bang, which was first predicted by George Gamow and his colleagues in the 1940s. If the Big Bang had really occurred, this radiation should be permeating the entire universe and should be detectable with a microwave antenna. The Princeton group soon met with Penzias and Wilson to compare notes, and both groups realized that the "noise" from the Bell Labs antenna was the cosmic microwave background—the first strong evidence that the Big Bang really did happen. Penzias and Wilson received the 1978 Nobel Prize in physics for their discovery of the cosmic microwave background.

Figure 17.6

Arno Penzias and Robert Wilson, discoverers of the cosmic microwave background, with the Bell Labs microwave antenna.

The cosmic microwave background is radiation left over from the Big Bang.

The cosmic microwave background consists of photons arriving at Earth directly from the end of the era of nuclei, when the universe was about 380,000 years old. Because neutral atoms finally could remain stable, they captured most of the

electrons in the universe. With no more free electrons to block them, the photons from that epoch have flown unobstructed through the universe ever since (Figure 17.7). When we observe the cosmic microwave background, we essentially are seeing back to a time when the universe was only 380,000 years old. In that sense, we are seeing light from the most distant regions of the observable universe—only 380,000 light-years from our cosmological horizon **[Section 15.2]**.

Because the cosmic microwave background came from the heat of the universe itself, it should have an essentially perfect thermal radiation spectrum **[Section 5.2]**. When this radiation first broke free 380,000 years after the Big Bang, the temperature of the universe was about 3000 K, which is similar to a red giant star's surface. The spectrum of the cosmic microwave background therefore originally peaked in visible light, just like the thermal radiation from a red star, with wavelengths of a few hundred nanometers. However, the universe has expanded by a factor of about 1000 since that time, stretching the wavelengths of these photons by the same amount **[Section 15.2]**. Their wavelengths are now about a millimeter, squarely in the microwave portion of the spectrum and corresponding to a temperature of a few degrees above absolute zero.

The cosmic microwave background—the heat of the universe itself—has a perfect thermal radiation spectrum corresponding to a temperature of 2.73 K.

In the early 1990s, a NASA satellite called the *Cosmic Background Explorer (COBE)* was launched to test these ideas about the cosmic microwave background. The results were a stunning success for the Big Bang theory. As shown in Figure 17.8, the cosmic microwave background does indeed have a perfect thermal radiation spectrum, with a peak corresponding to a temperature of 2.73 K, less than 3 K above absolute zero.

think about it Suppose the cosmic microwave background did not really come from the heat of the universe itself but instead came from many individual stars and galaxies. Explain why, in that case, we would not expect it to have a perfect thermal radiation spectrum. How does the spectrum of the cosmic microwave background lend support to the Big Bang theory?

COBE achieved an even greater success mapping the temperature of the cosmic microwave background in all directions. It was already known that the cosmic microwave background is extraordinarily uniform throughout the universe. Conditions in the early universe must have been extremely uniform to produce such a smooth radiation field. For a time, this uniformity was considered a strike against the Big Bang theory because, as we discussed in Chapters 15 and 16, the universe must have contained some regions of enhanced density in order to *explain the formation of galaxies*. The *COBE* measurements restored confidence in the Big Bang theory because they showed that the cosmic microwave background is *not quite* perfectly uniform. Instead, its temperature varies very slightly from one place to another by a few parts in 100,000.

More recently, NASA's *Wilkinson Microwave Anisotropy Probe (WMAP)* has provided further confirmation of the small temperature variations, with a map of the cosmic microwave background first released in 2003 (Figure 17.9). These variations in temperature indicate that the density of the early universe really did differ slightly from place to place. The seeds of structure formation were indeed present during the era of nuclei.

Figure 17.7 MA interactive figure

Photons (yellow squiggles) frequently collided with free electrons during the era of nuclei and thus could travel freely only after electrons became bound into atoms. The photons released at the end of the era of nuclei, when the universe was about 380,000 years old, make up the cosmic microwave background. Precise measurements of these microwaves tell us what the universe was like at this moment in time.

Figure 17.8

This graph shows the near-perfect agreement between measurements of the cosmic microwave background (dots) recorded by NASA's *COBE* satellite and a theoretically calculated thermal radiation spectrum (smooth curve) for a temperature of 2.73 K. This excellent fit is important evidence in favor of the Big Bang theory.

Figure 17.9 MA interactive photo

This all-sky map shows temperature differences in the cosmic microwave background measured by *WMAP*. The background temperature is about 2.73 K everywhere, but the brighter regions of this picture are about 0.0001 K hotter than the darker regions—indicating that the early universe was slightly lumpy at the end of the era of nuclei. We are essentially seeing what the universe was like at the surface marked "380,000 years" in Figure 17.5. Gravity later drew matter toward the centers of these lumps, forming the structures we see in the universe today.

The discovery of density enhancements bolstered the idea that some of the dark matter consists of WIMPs that we have not yet identified **[Section 16.2]** and that the gravity of this dark matter drove the formation of structure in the universe. Regions of enhanced density can grow into galaxies because the extra gravity in these regions draws matter together even while the rest of the universe expands. The greater the density enhancements, the faster matter should have collected into galaxies.

Maps of the cosmic microwave background reveal the density enhancements from which galaxies and larger structures later formed.

Detailed calculations show that, to explain the fact that galaxies formed within a few billion years, the density enhancements at the end of the era of nuclei must have been significantly greater than suggested by the temperature variations in the cosmic microwave background. Because WIMPs are weakly interacting and do not interact with photons, we do not expect them to influence the temperature of the cosmic microwave background directly. However, the gravity of the WIMPs can collect ordinary matter into clumps that *do* interact with photons. The small density enhancements detected by microwave telescopes therefore appear to echo much larger density enhancements made up of WIMPs. Careful modeling of these temperature variations shows that they are consistent with dark-matter density enhancements large enough to account for the structure we see in the universe today.

cosmic Calculations 17.1

Temperature of Background Radiation

As shown in Figure 17.8, the spectrum of the cosmic microwave background is a nearly perfect thermal radiation spectrum with a peak wavelength of about 1.1 millimeters. We can therefore use Wien's law (see Cosmic Calculations 5.1) to estimate the temperature of this radiation that fills the universe. Recall that Wien's law states

$$\lambda_{max} \approx \frac{2{,}900{,}000}{T(\text{Kelvin})}\ \text{nm}$$

where λ_{max} is the wavelength (in nanometers) of maximum intensity. We can solve this expression for T by multiplying both sides by T and dividing both sides by λ_{max}:

$$T(\text{Kelvin}) \approx \frac{2{,}900{,}000\ \text{nm}}{\lambda_{max}}$$

If you remember that 10^6 nm = 1 mm, you'll see that 1.1 millimeters is 1.1×10^6 nm. Using this value, we find

$$T(\text{Kelvin}) \approx \frac{2{,}900{,}000\ \text{nm}}{1.1 \times 10^6\ \text{nm}} \approx 2.6\ \text{K}$$

A more exact calculation shows that the temperature of the cosmic microwave background is 2.73 K.

• How do the abundances of elements support the Big Bang theory?

The discovery of the cosmic microwave background in 1965 quickly solved another long-standing astronomical problem: the origin of helium. Everywhere in the universe, about one-quarter of the mass of ordinary matter (not including dark matter) is helium. The Milky Way's helium fraction is about 28%, and no galaxy has a helium fraction lower than 25%. A small proportion of this helium comes from hydrogen fusion in stars, but most does not: Fusion of hydrogen to helium in stars could have produced only about 10% of the observed helium.

The majority of the helium in the universe must already have been present when stars and galaxies first began to form. In other words, the universe itself must once have been hot enough to fuse hydrogen into

helium. The current microwave background temperature of 2.73 K tells us precisely how hot the universe was in the distant past and exactly how much helium it should have made. The result—25% helium—is another impressive success of the Big Bang theory.

Helium Formation in the Early Universe To see why 25% of ordinary matter became helium, we need to understand what protons and neutrons were doing during the 5 minutes that marked the era of nucleosynthesis. Early in this era, when the universe's temperature was 10^{11} K, nuclear reactions could convert protons into neutrons, and vice versa. When the universe was hotter than 10^{11} K, these reactions kept the numbers of protons and neutrons nearly equal. But as the universe cooled, neutron–proton conversion reactions began to favor protons.

Neutrons are slightly more massive than protons, and therefore reactions that convert protons to neutrons require energy to proceed (in accordance with $E = mc^2$). As the temperature fell below 10^{11} K, the required energy for neutron production was no longer readily available, so the rate of these reactions slowed. In contrast, reactions that convert neutrons into protons release energy and thus are unhindered by cooler temperatures. By the time the temperature of the universe fell to 10^{11} K, protons began to outnumber neutrons because the conversion reactions ran only in one direction. Neutrons changed into protons, but the protons didn't change back.

For the next few minutes, the universe was still hot and dense enough for nuclear fusion to operate. Protons and neutrons constantly combined to form *deuterium*—the rare form of hydrogen nuclei that contains a neutron in addition to a proton—and deuterium nuclei fused to form helium (Figure 17.10). However, during the early part of the era of nucleosynthesis, the helium nuclei were almost immediately blasted apart by one of the many gamma rays that filled the universe.

The Big Bang theory predicts that the universe should have a chemical composition of 75% hydrogen and 25% helium by mass, which agrees with the observed composition.

Fusion began to create long-lasting helium nuclei when the universe was about 1 minute old and had cooled to a temperature at which it contained few destructive gamma rays. Calculations show that the proton-to-neutron ratio at this time should have been about 7 to 1, and

Figure 17.10

During the 5-minute-long era of nucleosynthesis, virtually all the neutrons in the universe fused with protons to form helium-4. This figure illustrates one of several possible reaction chains.

specialTopic | The Steady State Universe

ALTHOUGH THE BIG BANG THEORY is widely accepted among scientists today, alternative ideas have been proposed and considered. One of the cleverest alternatives, developed in the late 1940s, was called the *steady state universe*. This hypothesis accepted the fact that the universe is expanding but rejected the idea of a Big Bang, instead postulating that the universe is infinitely old. The steady state hypothesis may seem paradoxical at first: If the universe has been expanding forever, shouldn't every galaxy be infinitely far away from every other galaxy? Proponents of the steady state universe answered by claiming that new galaxies continually form in the gaps that open up as the universe expands, thereby keeping the same average distance between galaxies at all times. In a sense, the steady state hypothesis said that the creation of the universe is an ongoing and eternal process rather than one that happened all at once with a Big Bang.

Two key discoveries caused the steady state hypothesis to lose favor. First, the 1965 discovery of the cosmic microwave background matched a prediction of the Big Bang theory but was not adequately explained by the steady state hypothesis. Second, a steady state universe should look about the same at all times, which is inconsistent with observations showing that galaxies at great distances look younger than nearby galaxies. As a result of these predictive failures, most astronomers no longer take the steady state hypothesis seriously.

Figure 17.11

Calculations show that protons outnumbered neutrons 7 to 1, which is the same as 14 to 2, during the era of nucleosynthesis. The result was 12 hydrogen nuclei (individual protons) for each helium nucleus. Thus, the hydrogen-to-helium mass ratio is 12 to 4, which is the same as 75% to 25%. The agreement between this prediction and the observed abundance of helium is important evidence in favor of the Big Bang theory.

nearly all the available neutrons should have become incorporated into nuclei of helium-4. Figure 17.11 shows that, based on the 7-to-1 ratio of protons to neutrons, the universe should have had a composition of 75% hydrogen and 25% helium by mass at the end of the era of nucleosynthesis.

The Big Bang theory therefore makes a very concrete prediction about the chemical composition of the universe: It should be 75% hydrogen and 25% helium by mass. The fact that observations confirm this predicted ratio of hydrogen to helium is another striking success of the Big Bang theory.

think about it Briefly explain why it should not be surprising that some galaxies contain a little more than 25% helium, but why it would be very surprising if some galaxies contained less. (*Hint:* Think about how the relative amounts of hydrogen and helium in the universe are affected by fusion in stars.)

Abundances of Other Light Elements Why didn't the Big Bang produce heavier elements? By the time stable helium nuclei formed, when the universe was about a minute old, the temperature and density of the rapidly expanding universe had already dropped too far for a process like carbon production (three helium nuclei fusing into carbon **[Section 12.2]**) to occur. Reactions between protons, deuterium nuclei, and helium were still possible, but most of these reactions led nowhere. In particular, fusing two helium-4 nuclei results in a nucleus that is unstable and falls apart in a fraction of a second, as does fusing a proton to a helium-4 nucleus.

Rapid cooling and expansion of the early universe halted nuclear fusion before the universe could produce elements much heavier than helium.

A few reactions involving hydrogen-3 (also known as *tritium*) or helium-3 can create long-lasting nuclei. For example, fusing helium-4 and hydrogen-3 produces lithium-7. However, the contributions of these reactions to the overall composition of the universe were minor because hydrogen-3 and helium-3 were so rare. Models of element production in the early universe show that, before the cooling of the universe halted fusion entirely, such reactions generated only trace amounts of lithium, the next lightest element after helium. Aside from hydrogen, helium, and lithium, all other elements were forged much later in the nuclear furnaces of stars. (Beryllium and boron, which are heavier than lithium but lighter than carbon, were created when high-energy particles broke apart heavier nuclei that formed in stars.)

The Density of Ordinary Matter Calculations made with the Big Bang model allow scientists to estimate the density of ordinary matter in the universe from the observed amount of deuterium in the universe today. Remember that, during the era of nucleosynthesis, protons and neutrons first fused into deuterium and deuterium nuclei then fused into helium. The fact that some deuterium nuclei still exist in the universe indicates that this process stopped before all the deuterium nuclei were used up. The amount of deuterium in the universe today therefore tells us about the density of protons and neutrons during the era of nucleosynthesis: The higher the density, the more efficiently fusion would have proceeded. In other words, a higher density in the early universe

would have left less deuterium in the universe today, and a lower density would have left more deuterium.

Observations show that about one out of every 40,000 hydrogen atoms contains a deuterium nucleus—that is, a nucleus with a neutron in addition to its proton. Calculations based on this deuterium abundance show that the density of ordinary matter in the universe is about 4% of the critical density (Figure 17.12). (Recall that the critical density is equal to the density of matter required to stop the expansion of the universe in the absence of dark energy **[Section 16.4]**.) Similar calculations based on the observed abundance of lithium and helium-3 support this conclusion, adding to our confidence in the Big Bang model.

The abundances of light elements indicate that the overall amount of ordinary matter is much less than the total amount of dark matter.

These results also lead to an astonishing prediction about the nature of dark matter. Recall that the overall density of the universe appears to be close to 25% of the critical density **[Section 16.4]**. Because this is about six times as large as the 4% of the critical density that we find for ordinary matter, we conclude that the universe contains about six times as much dark matter as it does ordinary matter. Unless we are missing something fundamental in our understanding of these issues, the Big Bang model predicts that still-undiscovered subatomic particles such as WIMPs constitute the majority of the universe's mass. That is why most astronomers think that dark matter consists of WIMPs or something similar to them, and why many scientists are actively trying to find ways to detect WIMPs and learn about their properties.

think about it The ideas in this section point to a rather amazing fact: Although we have yet to discover any WIMPs, we suspect they dominate the total mass of the universe. Briefly explain how this is possible, and comment on how confident we can be that WIMPs make up the bulk of dark matter.

Figure 17.12

This graph shows how the measured abundances of deuterium, helium-3, and lithium-7 lead to the conclusion that the density of ordinary matter is about 4% of the critical density. The three horizontal swaths show measured abundances; the thickness of each swath represents the range of uncertainty in the measurements. (The upper edge of the blue swath indicates the upper limit on the helium-3 abundance; a lower limit has not yet been established.) The three curves represent models based on the Big Bang theory; these curves show how the abundance of each type of nucleus is expected to depend on the density of ordinary matter in the universe. Notice that the predictions (curves) match up with the measurements (horizontal swaths) only in the gray vertical strip, which represents a density of about 4% of the critical density.

17.3 The Big Bang and Inflation

The Big Bang model relies heavily on our knowledge of particle physics, which has been tested to temperatures of 10^{15} K, corresponding to temperatures at the end of the electroweak era, when the universe was a mere 10^{-10} second old. Our knowledge of earlier times rests on a weaker foundation because we are less certain of the physical laws at work. In fact, the best laboratory for studying the laws of physics at such high temperatures is the Big Bang itself.

Different models of how matter might behave at such high energies predict different outcomes for the universe we see today. If a particular model predicts that our universe should look different from the way it really does, then that model must be wrong. On the other hand, if a new model of particle physics explains some previously unexplained aspects of the universe, then it may be on the right track. The grand unified theories of particle physics discussed in Section 17.1 have not yet been confirmed, but many scientists suspect that these theories are on the right track for just this reason. In particular, the grand unified theories suggest that the universe at a very early age underwent the dramatic burst of expansion that we call *inflation*, and inflation seems to explain several key aspects of our universe that are otherwise left unexplained by the Big Bang theory.

• What aspects of the universe were originally unexplained by the Big Bang model?

The Big Bang theory has gained wide acceptance because of the strong evidence from the cosmic microwave background and the measured abundances of light elements in the universe. However, the theory in its simplest form leaves several major aspects of our universe unexplained. Three of the most pressing questions are the following:

The original Big Bang model left several important questions unanswered.

- **Where does structure come from?** Recall that our models of the formation of galaxies and larger structures all assume that gravity collected matter around regions of slightly enhanced density in the early universe. Explaining the origin of structure requires that the Big Bang must have somehow produced these slight density enhancements. The subtle temperature differences seen in the cosmic microwave background (see Figure 17.9) tell us that regions of enhanced density did indeed exist at the end of the era of nuclei, when the universe was 380,000 years old. But we still need to explain where the density enhancements came from.
- **Why is the large-scale universe so uniform?** Although the slight temperature variations in the cosmic microwave background show that the universe is not *perfectly* uniform on large scales, the overall smoothness is nonetheless remarkable. Observations of the cosmic microwave background tell us that the density of the universe at the end of the era of nuclei varied from place to place by no more than about 0.01%, and this uniformity explains why distant reaches of the universe look so similar today. Without inflation, the Big Bang theory does not explain these observations.
- **Why is the density of the universe close to the critical density?** The total density of dark matter plus dark energy in the universe **[Section 16.4]** appears to be remarkably close to the critical density—so close that it is difficult to consider it a coincidence. After all, there is no obvious reason why the density could not have been, say, 1000 times the critical density or 0.0000001 times the critical density. Without inflation, the Big Bang model is unable to explain the near-critical density of the universe as anything other than a chance occurrence.

• How does inflation explain these features of the universe?

Physicist Alan Guth realized in 1981 that grand unified theories could potentially answer all three questions. These theories predict that the separation of the strong force from the GUT force should have released enormous amounts of energy, causing the universe to expand dramatically, perhaps by a factor of 10^{30} in less than 10^{-36} second. This dramatic expansion is what we call *inflation*. Incredible as it may seem, we now suspect that the large-scale properties of the universe today were shaped by inflation that occurred during the first trillion-trillion-trillionth of a second after the Big Bang.

Structure: Giant Quantum Fluctuations To understand how inflation explains the origin of structure, we need to recognize a special feature of energy fields. Laboratory-tested principles of quantum mechanics tell us that on very small scales the energy fields at any

point in space are always fluctuating. The distribution of energy through space is therefore very slightly irregular, even in a complete vacuum. The tiny quantum "ripples" that make up the irregularities can be characterized by a wavelength that corresponds roughly to their size. In principle, quantum ripples in the very early universe could have been the seeds for density enhancements that later grew into galaxies. However, the wavelengths of the original ripples were far too small to explain density enhancements like those we see imprinted on the cosmic microwave background.

Inflation would have stretched tiny quantum ripples to enormous sizes, allowing them to become the density enhancements around which galaxies later formed.

Inflation would have dramatically increased the wavelengths of these quantum fluctuations. The fantastic growth of the universe during the period of inflation would have stretched tiny ripples from a size smaller than an atomic nucleus to the size of our solar system (Figure 17.13), making them large enough to become the density enhancements from which galaxies and larger structures later formed. Amazingly, the structure of today's universe may have started as tiny quantum fluctuations just before the period of inflation.

Figure 17.13

During inflation, ripples in spacetime would have stretched by a factor of perhaps 10^{30}. The peaks of these ripples then would have become the density enhancements that produced all the structure we see in the universe today.

Uniformity: Equalizing Temperatures and Densities The idea that different parts of the universe look very similar may seem quite natural, but on further inspection the uniformity of the universe becomes difficult to explain. Imagine observing the cosmic microwave background in a certain part of the sky. These microwaves have traveled through the universe since the end of the era of nuclei, just 380,000 years after the Big Bang. You are therefore seeing a region of the universe as it was some 14 billion years ago, when the universe was only 380,000 years old. Now imagine turning around and looking at the background radiation coming from the opposite direction. You are also seeing this region at an age of 380,000 years, and it looks virtually identical in temperature and density. The surprising part is this: The two regions are billions of light-years apart on opposite sides of our observable universe, but we are seeing them as they were when they were only 380,000 years old. They can't possibly have exchanged light or any other information; a signal traveling at the speed of light from one to the other would barely have started its journey. So how did they come to have the same temperature and density?

Inflation explains large-scale uniformity by saying that distant regions of our observable universe today were once close enough to exchange radiation.

Inflation answers this question by saying that even though the two regions cannot have had any contact *since* the time of inflation, they were in contact prior to that time. Before the onset of inflation when the universe was 10^{-38} second old, the two regions were less than 10^{-38} light-seconds away from one another. Radiation traveling at the speed of light would have had time to bounce between the two regions, and this exchange of energy equalized their temperatures and densities. Inflation then pushed these equalized regions to much greater distances, far out of contact with one another. Like criminals getting their stories straight before being locked in separate jail cells, the two regions (and all other parts of the observable universe) came to the same temperature and density before inflation spread them far apart.

Because inflation caused different regions of the universe to separate so vastly in such a short period of time, many people wonder whether it violates Einstein's theories saying that nothing can move

Figure 17.14

The three possible categories of overall geometry for the universe. Keep in mind that the real universe has one of these "shapes" in more dimensions than we can see.

faster than the speed of light. It does not, because nothing actually *moves* through space as a result of inflation or the ongoing expansion of the universe. Instead, the expansion of the universe is the expansion of *space itself*. Objects may be separating from one another at a speed faster than the speed of light, but no matter or radiation is able to travel between them during that time. In essence, inflation opens up a huge gap in space between objects that were once close together. The objects get very far apart, but nothing ever travels between them at a speed that exceeds the speed of light.

Density: Balancing the Universe The third question answered by inflation asks why the matter density of the universe is so close to the critical density. Another way to say that the universe's density is close to critical is to say that the overall geometry of the universe is remarkably "flat." To understand this idea, we must consider the overall geometry of the universe in a little more detail.

Recall that Einstein's general theory of relativity tells us that gravity can curve the structure of spacetime **[Section 13.3]**. Although we cannot visualize this curvature in all three dimensions of space (or all four dimensions of spacetime), we can detect its presence by its effects on light. For example, observations of gravitational lensing **[Section 16.2]** tell us that we are seeing light that has passed through a curved region of space. Although the curvature of the universe can vary from place to place, the universe as a whole must have some overall shape. Almost any shape is possible, but all the possibilities fall into just three general categories (Figure 17.14). Using analogies to objects that we can see in three dimensions, scientists refer to these three categories of shape as *flat* (or critical), *spherical* (or closed), and *saddle-shaped* (or open).

According to general relativity, the overall geometry would be flat if the matter density of the universe were precisely equal to the critical density, in which case the kinetic energy of expansion would precisely balance the universe's overall gravitational pull. In the absence of dark energy, any imbalance in these energies causes curvature of spacetime, and deviations from precise balance grow more severe as the universe evolves. For example, if the universe had been 10% denser at the end of the era of nuclei, it would have collapsed long ago. On the other hand, if it had been 10% less dense at that time, galaxies would never have formed before expansion spread all the matter too thin. The universe had to start out remarkably balanced to be even remotely close to flat today.

Inflation predicts that the overall geometry of the universe should appear flat, and hence that the overall density of matter and energy should equal the critical density.

Inflation can explain this precise balance by its effects on the geometry of the universe. In terms of Einstein's theory, the effect of inflation on spacetime curvature is similar to the flattening of a balloon's surface when you blow into it (Figure 17.15). The flattening of space during the period of inflation would have been so enormous that any curvature the universe might have had previously would be noticeable only on size scales much larger than the observable universe. Inflation therefore predicts that the overall geometry of the universe should appear perfectly flat, in which case the overall density of matter plus energy should be precisely equal to the critical density.

The fine balance predicted by inflation turns out to be both a success and a potential pitfall of the inflation theory. On one hand, it explains how the universe managed to have a density just right to allow the birth of galaxies. On the other hand, its prediction of a perfectly flat universe seems to disagree with observations showing that the total density of matter (including dark matter) is only about 25% of the critical density.

Dark energy might explain this shortfall in the density of dark matter. Remember that Einstein's theory of relativity tells us that mass can be transformed into energy and vice versa, which means that energy must be able to curve spacetime in the same way that mass can curve spacetime (see Special Topic: General Relativity and Curvature of Spacetime, page 372). The dark energy associated with a large-scale repulsive force can therefore compensate for the shortfall in the matter density, making the present-day universe flatter than it would otherwise be. Remarkably, the supernova measurements indicating that the expansion of the universe is accelerating **[Section 16.4]** also show that the strength of the implied repulsive force is about right to render the universe perfectly flat, just as inflation predicts. In other words, the total density of matter and dark energy together may indeed be precisely equal to the critical density.

Figure 17.15

As a balloon expands, its surface seems increasingly flat to an ant crawling along it. Inflation is thought to have made the universe seem flat in a similar way.

• How can we test the idea of inflation?

We've seen that inflation answers some outstanding mysteries about the universe, but did it really happen? We cannot directly observe the universe at the very early time when inflation is thought to have occurred. Nevertheless, we can test the idea of inflation by exploring whether its predictions are consistent with our observations of the universe at later times. Scientists are just beginning to test inflation, but the findings to date are consistent with the idea that an early inflationary episode made the universe uniform and flat while planting the seeds of structure formation.

Observed patterns in the temperature of the cosmic microwave background are consistent with the idea of inflation and reveal details about the universe's geometry, composition, and age.

The strongest tests of inflation so far come from detailed studies of the cosmic microwave background, particularly of the map made by the *WMAP* satellite (see Figure 17.9). Remember that this map shows tiny temperature differences corresponding to density variations in the universe at the end of the era of nuclei, when the universe was about 380,000 years old. However, according to the theory of inflation, these density enhancements were actually created much earlier, when inflation caused tiny quantum ripples to expand into seeds of structure. Careful observations of the temperature variations in the microwave background can therefore tell us about the structure of the universe during its first instant of existence.

Figure 17.16 shows an analysis of the temperature variations observed by *WMAP* in the cosmic microwave background. The graph shows how the typical temperature differences between patches of sky depend on their angular size on the celestial sphere. The dots represent data from the observations, and the red curve shows the inflation-based model that best fits the observations. This model makes specific predictions not only about the data shown in the figure, but also about other characteristics of our universe such as its overall geometry, composition, and age. In a sense, these new observations of the cosmic microwave background are

Figure 17.16

This graph shows how detailed analysis of temperature differences in the cosmic microwave background supports the idea of inflation. The data points indicate how the typical temperature differences between patches of sky depend on their angular size on the celestial sphere. The red curve shows the prediction of a model that relies on inflation to produce a universe whose ordinary matter density, dark matter density, and expansion rate are all similar to their observed values. Close agreement between the data points and the model indicates that the universe we live in has many of the characteristics predicted by that model.

revealing the characteristics of the seeds from which our universe has grown. To the extent that we have been able to observe these seeds, their nature aligns well with the universe we observe about us at the present time. According to the model shown in Figure 17.16, today's universe should have the following features:

- The overall geometry is flat, implying that the total mass-energy of the universe is equivalent to the critical density.
- The density of ordinary matter is 4.6% of the critical density, in agreement with observations of deuterium in the universe **[Section 17.2]**.
- The total matter density is 28% of the critical density. Subtracting the 4.6% for ordinary matter, we conclude that dark matter, probably in the form of weakly interacting massive particles, makes up about 23% of the critical density, in agreement with what we infer from measurements of the masses of clusters of galaxies **[Section 16.2]**.
- The combination of a flat geometry and a matter density lower than the critical density implies the existence of a repulsive force due to dark energy that currently accelerates the expansion, in agreement with observations of distant supernovae **[Section 16.4]**. Because the total mass-energy of the universe is the critical density, and matter accounts for only 28% of this, dark energy must account for the remaining 72% of the mass-energy of the universe.
- The universe's age should be about 13.7 billion years at the current microwave temperature of 2.73 K, in agreement with what we infer from Hubble's constant **[Section 15.2]** and the ages of the oldest stars **[Section 11.3]**.

The bottom line is that, all things considered, inflation does a remarkable job of explaining features of our universe that are otherwise unaccounted for in the Big Bang theory. Many astronomers and physicists therefore suspect that some process akin to inflation did affect the early universe, but the details of the interaction between high-energy particle physics and the evolving universe remain unclear. If these details can be worked out successfully, we face an amazing prospect—a breakthrough in our understanding of the very smallest particles, achieved by studying the universe on the largest observable scales.

17.4 Observing the Big Bang for Yourself

You might occasionally read an article in a newspaper or a magazine questioning whether the Big Bang really happened. We will never be able to prove with absolute certainty that the Big Bang theory is correct. However, no one has come up with any other model of the universe that so successfully explains so much of what we see. As we have discussed, the Big Bang model makes at least two specific predictions that we have observationally verified: the characteristics of the cosmic microwave background and the composition of the universe. It also explains many other features of the universe. So far, we know of nothing that is inconsistent with the Big Bang model.

The Big Bang theory's very success has also made it a target for respected scientists, skeptical nonscientists, and crackpots alike. The nature of scientific work requires that we test established wisdom to make sure it is valid. A sound scientific disproof of the Big Bang theory would be a discovery of great importance. However, stories touted in the news media as disproofs of the Big Bang usually turn out to be disagreements over details rather than fundamental problems with the theory itself. Yet scientists must keep refining the theory and tracking down disagreements, because once in a while a small disagreement blossoms into a full-blown scientific revolution.

You don't need to accept all you have read without question. The next time you contemplate the universe's origins, try an experiment for

specialTopic | How Will the Universe End?

ACCORDING TO THE BIG BANG THEORY, time and space have a beginning in the Big Bang. Do they also have an end? If we live in a recollapsing universe **[Section 16.4]**, the answer is clearly yes. Sometime in the distant future, the universal expansion will cease and reverse, and the universe will eventually come to an end in a fiery "Big Crunch." However, it now appears unlikely that we live in a recollapsing universe, in which case the universe seems destined to expand forever.

If dark energy is real, our Local Group of galaxies will become increasingly isolated as the acceleration of the universe carries the more distant galaxies ever faster away from us. Some scientists have speculated that the repulsive force of dark energy might even strengthen with time. In that case, the galaxies of the Local Group will someday separate, and the growing repulsive force could eventually tear apart our galaxy, our solar system, and even matter itself in a catastrophic event sometimes called the "Big Rip." However, the Big Rip is quite speculative; a more plausible scenario for the end of a perpetually expanding universe proceeds as follows.

The star–gas–star cycle in galaxies cannot continue forever, because not all the material is recycled. With each generation of stars, more mass becomes locked up in planets, brown dwarfs, white dwarfs, neutron stars, and black holes. About a trillion years from now, even the longest-lived stars will burn out, and the galaxies will fade into darkness.

At this point, the only new action in the universe will occur on the rare occasions when two objects—such as two brown dwarfs or two white dwarfs—collide within a galaxy. The vast distances separating star systems in galaxies make such collisions extremely rare. For example, the probability of our Sun (or the white dwarf that it will become) colliding with another star is so small that it would be expected to happen only once in a quadrillion (10^{15}) years. Forever is a long time, however, and even low-probability events will eventually happen many times. If a star system experiences a collision once in a quadrillion years, it will experience about 100 collisions in 100 quadrillion (10^{17}) years. By the time the universe reaches an age of 10^{20} years, star systems will have suffered an average of 100,000 collisions each, making a time-lapse history of any galaxy look like a cosmic game of pinball.

These multiple collisions will severely disrupt galaxies. As in any gravitational encounter, some objects lose energy in such collisions and some gain energy. Objects that gain enough energy will be flung into intergalactic space, where they will drift ever farther from all other objects with the expansion of the universe. Objects that lose energy will eventually fall to the galactic center, forming a gigantic black hole. The remains of the universe will consist of black holes with masses as great as a trillion solar masses widely separated from a few scattered planets, brown dwarfs, and stellar corpses. If Earth somehow survives, it will be a frozen chunk of rock in the darkness of the expanding universe, billions of light-years away from any other solid object.

If grand unified theories are correct, Earth cannot last forever. These theories predict that protons will eventually fall apart. The predicted lifetime of protons is extremely long: a half-life of at least 10^{32} years. However, if protons really do decay, then by the time the universe is 10^{40} years old, Earth and all other atomic matter will have disintegrated into radiation and subatomic particles.

The final phase may come through a mechanism proposed by Stephen Hawking. According to Hawking's theory, even black holes cannot last forever. Instead, they slowly "evaporate," their mass-energy turning into radiation. The process is so slow that we do not expect to see it from any existing black holes, but if Hawking is correct, then black holes in the distant future will disappear in brilliant bursts of radiation. The largest black holes will last the longest, but even trillion-solar-mass black holes will evaporate sometime after the universe reaches an age of 10^{100} years. From then on, the universe will consist only of individual photons and subatomic particles, each separated by enormous distances from the others. Nothing new will ever happen, and no events will ever occur that would allow an omniscient observer to distinguish past from future. In a sense, the universe will finally have reached the end of time.

Although this may sound depressing, keep in mind that 10^{100} years is an indescribably long time. As an example, imagine that you wanted to write on a piece of paper a number that consisted of a 1 followed by 10^{100} zeros (that is, the number $10^{10^{100}}$). It sounds easy, but a piece of paper large enough to fit all those zeros *would not fit in the observable universe* today. If that still does not alleviate your concerns, you may be glad to know that a few creative thinkers have speculated about ways in which the universe might undergo rebirth, even after the end of time.

yourself. Go outside on a clear night, look at the sky, and consider why it is dark.

see it for yourself How dark is the night sky where you live? Go outside and observe it on a clear, moonless night. Estimate the total number of stars that you can see. How many stars like those do you think it would take to completely cover the entire sky?

• Why is the darkness of the night sky evidence for the Big Bang?

If the universe were infinite, unchanging, and everywhere the same, then the entire night sky would blaze as brightly as the Sun. Johannes Kepler **[Section 3.3]** was one of the first people to reach this conclusion, but we now refer to the idea as **Olbers' paradox** after Heinrich Olbers, a German astronomer who described it in 1823.

If the universe were infinite, unchanging, and everywhere the same, then the entire night sky would be bright, because it would be completely covered with stars.

To understand Olbers' paradox, imagine that you are in a dense forest on a flat plain. If you look in any direction, you'll likely see a tree. If the forest is small, you might be able to see through some gaps in the trees to the open plains, but larger forests have fewer gaps (Figure 17.17). An infinite forest would have no gaps at all—a tree trunk would block your view along any line of sight.

The universe is like a forest of stars in this respect. In an unchanging universe with an infinite number of stars, we would see a star in every direction, making every point in the sky as bright as the Sun's surface. Even the presence of obscuring dust would not change this conclusion. The intense starlight would heat the dust over time until it also glowed like the Sun or evaporated away.

There are only two ways out of this dilemma. Either the universe has a finite number of stars, in which case we would not see a star in every direction, or it changes over time in some way that prevents us from seeing an infinite number of stars. For several centuries after Kepler first recognized the dilemma, astronomers leaned toward the first option. Kepler himself preferred to believe that the universe had a finite number of stars because he thought it had to be finite in space, with some kind of dark wall surrounding everything. Astronomers in the early 20th century preferred to believe that the universe was infinite in space but that we lived inside a finite collection of stars. They thought of the Milky Way as an island floating in a vast black void. However, subsequent observations showed that galaxies fill all of space more or less uniformly. We are therefore left with the second option: The universe changes over time.

The Big Bang theory is the best explanation we have for why the night sky is dark.

The Big Bang theory solves Olbers' paradox in a particularly simple way. It tells us that we can see only a finite number of stars because the universe began at a particular moment. While the universe may contain an infinite number of stars, we can see only those that lie within the observable universe, inside our cosmological horizon **[Section 15.2]**. There are other ways in which the universe could change over time and prevent us from

a In a large forest, a tree will block your view no matter where you look. Similarly, in an unchanging universe with an infinite number of stars, we would expect to see stars in every direction, making the sky bright even at night.

b In a small forest with a smaller number of trees, you can see open spaces beyond the trees. Because the night sky is dark, the universe must similarly have spaces in which we see nothing beyond the stars, which means either that the number of stars is finite or that the universe changes in a way that prevents us from seeing an infinite number of them.

Figure 17.17

Olbers' paradox can be understood by thinking of the view through a forest.

seeing an infinite number of stars, so Olbers' paradox does not *prove* that the universe began with a Big Bang. However, we must have some explanation for why the sky is dark at night, and no explanation besides the Big Bang also explains so many other observed properties of the universe so well.

the big picture

Putting Chapter 17 into Perspective

Our "big picture" is now about as complete as it gets. We've discussed the universe from Earth outward, and from the beginning to the end. When you think back on this chapter, keep in mind the following ideas:

- Predicting conditions in the early universe is straightforward, as long as we know how matter and energy behave under such extreme conditions.
- Our current understanding of physics allows us to reconstruct the conditions of the universe all the way back to the first 10^{-10} second. Our understanding is less certain back to 10^{-38} second. Beyond 10^{-43} second, we run up against the present limits of human knowledge.
- Although it may sound strange to talk about the universe during its first fraction of a second, our ideas about the Big Bang rest on a solid foundation of observational, experimental, and theoretical evidence. We cannot say with absolute certainty that the Big Bang really happened, but no other model has so successfully explained how our universe came to be as it is.

summary of key concepts

17.1 The Big Bang

- **What were conditions like in the early universe?**

The early universe was filled with radiation and elementary particles. It was so hot and dense that the energy of radiation could turn into particles of **matter** and **antimatter**, which then collided and turned back into radiation.

- **What is the history of the universe according to the Big Bang theory?**

The universe has been through a series of eras, each marked by unique physical conditions. We know little about the **Planck era**, when the four forces may have been unified. Gravity became distinct at the start of the **GUT era**, which may have ended with the rapid expansion called **inflation**. Electromagnetism and the weak force became distinct at the end of the **electroweak era**. Matter particles annihilated all the antimatter particles by the end of the **particle era**. Fusion of protons and neutrons into helium ceased at the end of the **era of nucleosynthesis**. Hydrogen nuclei captured all the free electrons, forming hydrogen atoms at the end of the **era of nuclei**. Galaxies began to form at the end of the **era of atoms**. The **era of galaxies** continues to this day.

17.2 Evidence for the Big Bang

- **How do we observe the radiation left over from the Big Bang?**

Microwave telescopes allow us to observe the **cosmic microwave background**—radiation left over from the Big Bang. Its spectrum matches the characteristics expected of the radiation released at the end of the era of nuclei, confirming a key prediction of the Big Bang theory.

- **How do the abundances of elements support the Big Bang theory?**

The Big Bang theory predicts the ratio of protons to neutrons during the era of nucleosynthesis, and from this predicts that the chemical composition of the universe should be about 75% hydrogen and 25% helium (by mass). This matches observations of the cosmic abundances, another confirmation of the Big Bang theory.

17.3 The Big Bang and Inflation

- **What aspects of the universe were originally unexplained by the Big Bang model?**

(1) The origin of the density enhancements that turned into galaxies and larger structures. (2) The overall smoothness of the universe on large scales. (3) The fact that the actual density of matter is close to the critical density.

- **How does inflation explain these features of the universe?**

(1) The episode of inflation stretched tiny, random quantum fluctuations to sizes large enough to become the density enhancements around which structures later formed. (2) The universe is smooth on large scales because, prior to inflation, everything we can observe today was close enough together for temperatures and densities to equalize. (3) Inflation caused the universe to expand so much that the observable universe appears geometrically flat, implying that its overall density of mass plus energy equals the critical density.

- **How can we test the idea of inflation?**

Models of inflation make specific predictions about the temperature patterns we should observe in the cosmic microwave background. The patterns seen in observations by microwave telescopes match those predicted by inflation.

17.4 Observing the Big Bang for Yourself

- **Why is the darkness of the night sky evidence for the Big Bang?**

Olbers' paradox tells us that if the universe were infinite, unchanging, and filled with stars, the sky would be everywhere as bright as the surface of the Sun, and it would not be dark at night. The Big Bang theory solves this paradox by telling us that the night sky is dark because the universe has a finite age, which means we can see only a finite number of stars in the sky.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 17 Visual Quiz at www.masteringastronomy.com.

This graph (repeated from Figure 17.12) shows the measured abundances of deuterium, helium-3, and lithium-7, along with the amounts predicted by the Big Bang model. These predictions depend on the density of ordinary matter in the universe. Answer the following questions based on the information provided in the graph.

1. How does the measured abundance of deuterium compare with the measured abundance of hydrogen?
   a. Deuterium is 40,000 times as abundant as hydrogen.
   b. Deuterium and hydrogen have roughly the same abundance.
   c. Hydrogen is between 4 and 5 times as abundant as deuterium.
   d. Hydrogen is 40,000 times as abundant as deuterium.
2. How does the measured abundance of lithium compare with the measured abundance of deuterium?
   a. Deuterium is between 3 and 4 times as abundant as lithium.
   b. Deuterium is between 30 and 40 times as abundant as lithium.
   c. Deuterium is between 300 and 400 times as abundant as lithium.
   d. Deuterium is between 1000 and 100,000 times as abundant as lithium.
3. What abundance of deuterium is predicted by a model in which the density of ordinary matter is 4% of the critical density?
   a. Deuterium is predicted to be 40,000 times as abundant as hydrogen.
   b. Deuterium is predicted to have the same abundance as hydrogen.
   c. The deuterium abundance is predicted to be about 4% of the hydrogen abundance.
   d. The deuterium abundance is predicted to be about 2.5×10^{-5} times that of hydrogen.
4. If you measured the abundance of deuterium in the universe to be 1% of the abundance of hydrogen, what would you conclude about the density of ordinary matter?
   a. The density of ordinary matter is slightly less than 0.1% of the critical density.
   b. The density of ordinary matter is slightly greater than 1% of the critical density.
   c. The density of ordinary matter is about 4% of the critical density.
   d. The density of ordinary matter is around 100% of the critical density.

exercises and problems

Mastering ASTRONOMY®

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Review Questions

1. What is *antimatter?* How were particle–antiparticle pairs created in the early universe? How were they destroyed?
2. Explain what we mean by the *Big Bang theory*.
3. Make a list of the major eras in the history of the universe, summarizing the important events thought to have occurred during each era.
4. Why can't our current theories describe the history of the universe during the *Planck era?*
5. What are the four forces that operate in the universe today? Why do we think there were fewer forces operating in the early universe?
6. What are *grand unified theories?* According to these theories, how many forces operated during the *GUT era?* How were these forces related to the four forces that operate today?
7. What do we mean by *inflation*, and when do we think it occurred?

8. Why do we think there was a slight imbalance between matter and antimatter in the early universe? What happened to all the antimatter, and when?
9. How long did the *era of nucleosynthesis* last? Explain why this era was so important in determining the chemical composition of the universe forever after.
10. When we observe the *cosmic microwave background*, at what age are we seeing the universe? How long have these microwave photons been traveling through space? Explain.
11. Briefly describe how the cosmic microwave background was discovered. How does the existence and nature of this radiation support the Big Bang theory?
12. How does the chemical abundance of helium in the universe support the Big Bang theory? Explain.
13. How do measurements of the abundances of deuterium and lithium tell us about the density of the universe, and why do they suggest that most dark matter consists of WIMPs?
14. Describe each of the three major questions left unanswered by the Big Bang theory without inflation, and explain how inflation answers each of them.
15. How can observations of the cosmic microwave background tell us about the universe at the much earlier time when inflation occurred? Summarize the geometry, composition, and age of the universe according to observations made to date.
16. What is *Olbers' paradox*, and how is it resolved by the Big Bang theory?

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

17. Although the universe today appears to be made mostly of matter and not antimatter, the Big Bang theory suggests that the early universe had nearly equal amounts of matter and antimatter.
18. According to the Big Bang theory, the cosmic microwave background was created when energetic photons ionized the neutral hydrogen atoms that originally filled the universe.
19. While the existence of the cosmic microwave background is consistent with the Big Bang theory, we can also easily explain it by assuming that it comes from individual stars and galaxies.
20. According to the Big Bang theory, most of the helium in the universe was created by nuclear fusion in the cores of stars.
21. The theory of inflation suggests that the structure of the universe today may have originated as tiny quantum fluctuations.
22. The fact that the night sky is dark tells us that the universe cannot be infinite, unchanging, and everywhere the same.
23. We'll never know whether inflation actually happened because our model for inflation doesn't make any predictions we can test.
24. In the distant past, the radiation that we call the cosmic microwave background actually consisted primarily of infrared light.
25. The main reason that the night sky is dark is that stars are generally so far away.
26. The cosmic microwave background is our main source of information about what the universe was like at an age of about 5 minutes.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. What is the current temperature of the universe? (a) absolute zero (b) a few degrees (c) a few thousand degrees
28. What is the charge of an antiproton? (a) positive (b) negative (c) neutral
29. What happens when a proton collides with an antiproton? (a) They repel each other. (b) They fuse together. (c) They convert into two photons.
30. Which of the following does *not* provide strong evidence for the Big Bang theory? (a) observations of the cosmic microwave background (b) observations of the amount of hydrogen in the universe (c) observations of the ratio of helium to hydrogen in the universe
31. If the current density of ordinary matter in the universe were 10 times as great as it is now, we would expect to observe (a) more deuterium. (b) less deuterium. (c) about the same amount of deuterium.
32. Which of the following does inflation help to explain? (a) the uniformity of the cosmic microwave background (b) the amount of helium in the universe (c) the temperature of the cosmic microwave background
33. Which of the following does inflation help to explain? (a) the origin of hydrogen (b) the origin of galaxies (c) the origin of atomic nuclei
34. Which of these pieces of evidence supports the idea that inflation really happened? (a) the enormous size of the observable universe (b) the large amount of dark matter that the universe contains (c) observations of the cosmic microwave background that indicate a flat geometry for the universe
35. What is the earliest time in the universe that we can directly observe? (a) a few hundred million years after the Big Bang (b) a few hundred thousand years after the Big Bang (c) a few minutes after the Big Bang
36. Which of these options is the best explanation for why the night sky is dark? (a) The universe is not infinite in space. (b) The universe has not always looked the way it looks today. (c) The distribution of matter in the universe is not uniform on very large scales.

Process of Science

37. *Unanswered Questions.* We have seen in this chapter that our understanding of the early universe remains incomplete. Briefly describe one important but unanswered question about the events that happened shortly after the Big Bang. If you think it will be possible to answer that question in the future, describe how we could find an answer, being as specific as possible about the evidence necessary to do so. If you think the question will never be answered, explain why you think it is impossible to answer.
38. *Darkness at Night.* Suppose you are Kepler, pondering the darkness of the night sky without any knowledge of the Big Bang or the expanding universe. Develop a hypothesis to explain the darkness of the night sky that does not depend on the Big Bang theory. Propose an experiment that scientists could perform today to test that hypothesis.

Group Work Exercise

39. *Testing the Big Bang Theory.* The Big Bang theory is widely accepted because it has successfully predicted many observed characteristics of our universe and because there are no observations that strongly conflict with the theory. In this exercise, you'll consider five hypothetical observations that are not predicted by the Big Bang theory:
    a. a star cluster with an age of 15 billion years
    b. a galaxy with an age of 10 million years
    c. a galaxy at a distance of 10 billion light-years whose spectrum is blueshifted
    d. a galaxy containing 90% hydrogen and 10% helium
    e. evidence for an increase of the cosmic microwave background temperature with time

Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Advocate* (argues in favor of the Big Bang theory), *Skeptic* (points out weaknesses in the Big Bang theory), and *Moderator* (leads group discussion and makes sure everyone contributes). For each observation, discuss whether it (1) could be explained with the Big Bang theory, (2) could be explained with a revision to the Big Bang theory, or (3) would force us to abandon the Big Bang theory. After listening to the *Advocate* and *Skeptic* discuss each discovery, the *Scribe* and *Moderator* should choose option (1), (2), or (3) and write down your team's reasoning for each observation.

Investigate Further

Short-Answer/Essay Questions

40. *Life Story of a Proton.* Tell the life story of a proton from its formation shortly after the Big Bang to its presence in the nucleus of an oxygen atom you have just inhaled. Your story should be creative and imaginative, but it should also demonstrate your scientific understanding of as many stages in the proton's life as possible. Your story should be three to five pages long.
41. *Creative History of the Universe.* The story of creation as envisioned by the Big Bang theory is quite dramatic, but it is usually told in a fairly straightforward, scientific way. Write a more dramatic telling of the story, in the form of a short story, play, or poem. Be as creative as you wish, but be sure to remain accurate according to the science as it is understood today.
42. *Re-Creating the Big Bang.* Particle accelerators on Earth can push particles to extremely large speeds. When these particles collide, the amount of energy associated with the colliding particles is much greater than the mass-energy these particles have when at rest. As a result, these collisions can produce many other particles out of pure energy. Explain in your own words how the conditions that occur in these accelerators are similar to the conditions that prevailed shortly after the Big Bang. Also, point out some of the differences between what happens in particle accelerators and what happened in the early universe.
43. *Betting on the Big Bang Theory.* If you had $100, how much money would you wager on the proposition that we have a reasonable scientific understanding of what the universe was like when it was 1 minute old? Explain the reasoning behind your choice.
44. *"Observing" the Early Universe.* The only way we have of studying the era of nucleosynthesis is through the abundances of the nuclei that it left behind. Explain why we will never be able to observe that era through direct detection of the radiation emitted at that time.
45. *Element Production in the Big Bang.* Nucleosynthesis in the early universe was unable to produce more than trace amounts of elements heavier than helium. Using the information in Figure 12.17, which shows the mass per nuclear particle for many different elements, explain why producing elements like lithium (3 protons), boron (4 protons), and beryllium (5 protons) was so difficult.
46. *Evidence for the Big Bang.* Alternatives to the Big Bang theory need to propose alternative explanations for many of the observations scientists have made of the universe. Make a list of at least seven observed features of the universe that are satisfactorily explained by the Big Bang theory when it is combined with the idea of inflation.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

47. *Energy from Antimatter.* The total annual U.S. power consumption is about 2×10^{20} joules. Suppose you could supply that energy by combining pure matter with pure antimatter. Estimate the total mass of matter–antimatter fuel you would need to supply the United States with energy for 1 year. How does that mass compare with the amount of matter in your car's gas tank? (A gallon of gas has a mass of about 4 kg.)
48. *Uniformity of the Cosmic Microwave Background.* The temperature of the cosmic microwave background differs by only a few parts in 100,000 across the sky. Compare that level of uniformity to the surface of a table in the following way. Consider a table that is 1 meter in size. How big would the largest bumps on that table be if its surface were smooth to the level of one part in 100,000? Could you see bumps of that size on the table's surface?
49. *Daytime at "Night."* According to Olbers' paradox, the entire sky would be as bright as the surface of a typical star if the universe were infinite in space, unchanging in time, and the same everywhere. However, conditions would not need to be quite that extreme for the "nighttime" sky to be as bright as the daytime sky.
    a. Using the inverse square law for light from Cosmic Calculations 11.1, determine the apparent brightness of the Sun in our sky.
    b. Using the inverse square law for light, determine the apparent brightness our Sun would have if it were at a distance of 10 billion light-years.
    c. From your answers to parts (a) and (b), estimate how many stars like the Sun would need to exist at a distance of 10 billion light-years for their total apparent brightness to equal that of our Sun.
    d. Compare your answer to part (c) with the estimate of 10^{22} stars in our observable universe given in Section 1.2. Use your answer to explain why the night sky is much darker than the daytime sky. How much larger would the total number of stars need to be for "night" to be as bright as day?

Discussion Questions

50. *The Moment of Creation.* You've probably noticed that, when discussing the Big Bang theory, we never talk about the very first instant. Even our most speculative theories at present take us back only to within 10^{-43} second of creation. Do you think it will *ever* be possible for science to consider the moment of creation itself? Will we ever be able to answer questions such as *why* the Big Bang happened? Defend your opinions.
51. *The Big Bang.* How convincing do you find the evidence for the Big Bang model of the universe's origin? What are the strengths of the theory? What does it fail to explain? Overall, do *you* think the Big Bang really happened? Defend your opinion.

Web Projects

52. *New Tests of the Big Bang Theory.* The satellites *COBE* and *WMAP* have provided striking confirmation of several predictions of the Big Bang theory. The more recent *Planck* mission was designed to test the Big Bang theory further. Use the Web to gather pictures and information about *COBE*, *WMAP*, and *Planck*. Write a one- to two-page report about the strength of the evidence compiled by *COBE* and *WMAP* and what we are learning from *Planck*.
53. *New Ideas About Inflation.* The idea of inflation solves many of the puzzles associated with the standard Big Bang theory, but we are still a long way from finding evidence confirming that inflation really occurred. Read a few recent articles that discuss some of the latest ideas about inflation and how we might test these ideas. Write a two- to three-page summary of your findings.

Part V at a Glance. Galaxy Evolution

All galaxies, including our Milky Way, developed as gravity pulled together matter in regions of the universe that started out slightly denser than surrounding regions. The central illustration depicts how galaxies formed over time, starting from the Big Bang in the upper left and proceeding to the present day in the lower right, as space gradually expanded according to Hubble's law.

1 Dramatic inflation early in time is thought to have produced large-scale ripples in the density of the universe. All the structure we see today formed as gravity drew additional matter into the peaks of these ripples. [Section 17.3]

Inflation may have stretched tiny quantum fluctuations into large-scale ripples.

2 Observations of the cosmic microwave background show us what the regions of enhanced density were like about 380,000 years after the Big Bang. [Section 17.2]

Photo by *WMAP*

Variations in the cosmic microwave background show that regions of the universe differed in density by only a few parts in 100,000.

3 Large-scale surveys of the universe show that gravity has gradually shaped early regions of enhanced density into a web-like structure, with galaxies arranged in huge chains and sheets. [Section 16.3]

Sloan Digital Sky Survey

The web-like patterns of structure observed in large-scale galaxy surveys agree with those seen in large-scale computer simulations of structure formation.

4 Within this large-scale web, galaxy formation began when gravity collected hydrogen and helium gas into blobby protogalactic clouds. [Section 15.3]

Photo of spiral galaxy M101

5 At least some elliptical galaxies formed when two spiral galaxies collided and merged. [Section 15.3]

Photo of elliptical galaxy M87

6 Dark matter is thought to drive galaxy formation. The gravity of dark matter seems to be what pulled gas into protogalactic clouds. It continues to cause galaxies to cluster and sometimes to collide. [Section 16.3]

Measurements indicate a large amount of invisible dark matter surrounds the visible stars in each galaxy.

7 Today, in the disks of spiral galaxies like the Milky Way, the star-gas-star cycle continues to produce new stars and planets from matter that was once in protogalactic clouds. [Section 14.2]

Photo of Orion Nebula

New stars and planetary systems—some perhaps much like our own—are currently forming in the Orion Nebula, 1500 light-years from Earth.

18

Life in the Universe

learning goals

18.1 Life on Earth
- When did life arise on Earth?
- How did life arise on Earth?
- What are the necessities of life?

18.2 Life in the Solar System
- Could there be life on Mars?
- Could there be life on Europa or other jovian moons?

18.3 Life Around Other Stars
- Are habitable planets likely?
- Are Earth-like planets rare or common?

18.4 The Search for Extraterrestrial Intelligence
- How many civilizations are out there?
- How does SETI work?

18.5 Interstellar Travel and Its Implications to Civilization
- How difficult is interstellar travel?
- Where are the aliens?

We have covered a lot of ground in this book, discussing fundamental questions about the nature and origin of our planet, our star, our galaxy, and our universe. But we have not yet discussed the most profound question of all: Are we alone? The universe contains worlds beyond imagination—more than 100 billion star systems in our galaxy alone, and some 100 billion galaxies in the observable universe—yet we do not know whether any world other than our own has ever been home to life.

In this chapter, we will discuss the possibility of life beyond Earth. We'll begin by considering the history of life on Earth, which will help us understand the prospects of finding life elsewhere. We'll then consider the possibility of finding microbial life elsewhere in our solar system or beyond, and examine efforts to search for extraterrestrial intelligence (SETI). Finally, we'll discuss the astonishing implications that the search for life may hold for our future.

essential preparation

1. How do we detect planets around other stars? **[Section 6.5]**
2. What unique features of Earth are important for life? **[Section 7.5]**
3. Why are Jupiter's Galilean moons geologically active? **[Section 8.2]**
4. What geological activity do we see on Titan and other moons? **[Section 8.2]**
5. What is the significance of the main sequence? **[Section 11.2]**

18.1 Life on Earth

It may seem that aliens are everywhere. Aliens abound in television shows and movies, and it's not hard to find Web sites claiming alien atrocities or a government conspiracy to hide alien corpses in "Area 51."

Despite their media popularity, any alien visitors have been sadly negligent in leaving scientific evidence of their trespass. Decades of scientific observation and study have not turned up a single piece of undeniable evidence that aliens have been here (see Special Topic, page 507). Why, then, do so many scientists believe it is worth the effort to search for life beyond Earth?

For a long time, the answer was simply that it seemed natural for other worlds to be inhabited. Belief in life on other worlds was common even among ancient Greek philosophers, and many famous scientists of the past few centuries took it as a given that intelligent beings exist on other planets. Kepler suggested that the Moon was inhabited, and William Herschel spoke of life on virtually all the planets in our solar system. Most famously, in the late 19th century, Percival Lowell claimed to see networks of canals on Mars, which he argued were the mark of an advanced civilization. Lowell's ideas inspired H. G. Wells to write *The War of the Worlds.*

Today, the question of life beyond Earth is subject to serious scientific research. This research has been spurred in part by the discovery of planets around other stars **[Section 6.5]**, which confirms that there are plenty of places to look for life beyond our own solar system. But new discoveries about life on Earth have also played an important role. In particular, three developments in the study of life on Earth have made it seem much more likely that life might exist elsewhere:

1. We have learned that life arose quite early in Earth's history, suggesting that life might also form quickly on other worlds with the right conditions.
2. Laboratory experiments have shown that the chemical constituents thought to have been common on the young Earth combine readily into complex organic molecules. These experiments suggest that life

Figure 18.1

Formation of sedimentary rock. Each layer represents a particular time and place in Earth's history and is characterized by fossils of organisms that lived in that time and place.

might have arisen through naturally occurring chemistry—in which case the same chemistry could have given rise to life on many other worlds.

3. We have discovered microscopic living organisms that probably could survive in conditions similar to those on at least some other worlds in our solar system, suggesting that the necessities of life may be common in the universe.

Because these three ideas are so important to understanding the modern science of life in the universe, often called *astrobiology,* let's examine each of them in greater detail. Along the way, we'll also discuss the nature and history of life on Earth. We will then be prepared to consider how we might search for life on other worlds.

• When did life arise on Earth?

The first of our three major ideas above is that life arose quite early on Earth. But how do we know? We learn about the history of life on Earth through the study of **fossils**, relics of organisms that lived and died long ago. Most fossils form when dead organisms fall to the bottom of a sea (or other body of water) and are gradually buried by layers of sediments. The sediments are produced by erosion on land and carried by rivers to the sea. Over millions of years, sediments pile up on the seafloor, and the weight of the upper layers compresses underlying layers into rock. Erosion or tectonic activity can later expose the fossils (Figure 18.1). In some places, such as the Grand Canyon, the sedimentary layers record hundreds of millions of years of Earth's history (Figure 18.2).

Figure 18.2

The rock layers of the Grand Canyon record more than 500 million years of Earth's history.

The key to reconstructing the history of life is to determine the dates at which fossil organisms lived. The *relative* ages of fossils found in different layers are easy to determine: Deeper layers formed earlier and contain more ancient fossils. Radiometric dating **[Section 6.4]** confirms these relative ages and gives us fairly precise absolute ages for fossils. Based on the layering of rocks and fossils, geologists divide Earth's history into a set of distinct intervals that make up what we call the **geological time scale**. Figure 18.3 shows the names of the various intervals on a timeline, along with numerous important events in Earth's history.

think about it How does the length of time during which animals and plants have lived on land compare to the length of time during which life has existed? How does the length of time during which humans have existed compare to the length of time since mammals and dinosaurs first arose?

Figure 18.3

The geological time scale. Notice that the lower timeline is an expanded view of the last portion of the upper timeline. The eons, eras, and periods are defined by changes observed in the fossil record. The absolute ages come from radiometric dating. (The *K–T event* is the geological term for the impact linked to the mass extinction of the dinosaurs **[Section 9.4]**.)

You might wonder why the geological time scale shows so much more detail in the last few hundred million years than it does for earlier times. The answer is that fossils become increasingly difficult to find as we look deeper into Earth's history, for three major reasons. First, older rocks are much rarer than younger rocks, because most of Earth's surface is geologically young. Second, even when we find very old rocks, they often have been subject to transformations (caused by heat and pressure) that would have destroyed any fossil evidence they may have contained. Third, all life prior to a few hundred million years ago was microscopic, and microscopic fossils are much more difficult to identify.

Despite these difficulties, geologists have found a few very old rocks that suggest life was already thriving on Earth 3.5 billion years ago, and possibly for several hundred million years before that. One strong line of evidence comes from rocks called *stromatolites,* which look strikingly similar to large microbial mats today (Figure 18.4). Careful analysis suggests that stromatolites were made by living organisms, and radiometric dating shows that some of them are nearly 3.5 billion years old.

Figure 18.4

Rocks called stromatolites offer evidence of microbial life as early as 3.5 billion years ago.

a These knee-high mats at Shark Bay, Western Australia, are colonies of microbes known as "living stromatolites."

b The bands visible in this section of a modern-day mat are formed by layers of sediment adhering to different types of microbes.

c This section of a 3.5-billion-year-old stromatolite shows a structure nearly identical to that of a living mat.

If organisms were advanced enough to build stromatolites 3.5 billion years ago, more primitive organisms must have lived even earlier. Some evidence supports this idea. More ancient rocks that have undergone too much change to leave fossils intact may still hold carbon that was once part of living organisms.

Fossil evidence suggests that life on Earth was thriving 3.5 billion years ago, and carbon isotope evidence may push that date back to 3.85 billion (or more) years ago.

Carbon has two stable isotopes: carbon-12, with six protons and six neutrons in its nucleus, and carbon-13, which has one extra neutron (see Figure 5.6). Living organisms incorporate carbon-12 slightly more easily than carbon-13. As a result, the fraction of carbon-13 is always a bit lower in fossils than in rock samples that lack fossils. All life and all fossils tested to date show the same characteristic ratio of the two carbon isotopes. Dating very ancient rocks can be difficult, but some rocks that are at least 3.85 billion years old show the same ratio of carbon-12 to carbon-13, suggesting that these rocks contain remnants of life, though it is possible that nonbiological processes could be responsible.

Could life have arisen even earlier? Until recently, many scientists thought that life (or, at least, the life that ultimately evolved into modern organisms) could not have arisen before the end of the *heavy bombardment*, about 3.9 billion years ago **[Section 6.4]**. The heavy bombardment was a time during which Earth should have been repeatedly struck by large asteroids or comets, and studies of craters on the Moon suggest that there was an especially strong *late heavy bombardment* toward the end of that time period. Past models suggested that the largest impacts would have completely vaporized the oceans and raised the global surface temperature high enough to melt the upper crust. In that case, these events would have been *sterilizing impacts* that would have killed off any life on Earth at the time. However, more recent models suggest that these effects were overstated, and that while large impacts would have sterilized substantial portions of our planet, microscopic life living underground and in some deep ocean environments could have survived.

If life did arise very early, evidence will be hard to find. The relatively few known rocks that date to earlier than 3.5 billion years ago have been so transformed by heat and pressure that any evidence they contain is likely to be controversial. Indeed, if the carbon isotope evidence really does indicate life some 3.85 billion years ago, the rarity of such old rocks suggests that life must have already been widespread on Earth by that time; otherwise, it would take extraordinary luck to have found the evidence.

Life seems to have arisen within a few hundred million years of Earth's birth.

To summarize, fossil evidence points to life on Earth thriving 3.5 billion years ago, and carbon isotope evidence may point to widespread life more than 3.85 billion years ago. Life could have arisen even earlier, though evidence would be hard to find. Still, no matter how we look at it, it seems that life on Earth arose within no more than a few hundred million years after Earth's birth about $4\frac{1}{2}$ billion years ago. Geologically speaking, that is a remarkably short time.

• How did life arise on Earth?

We have discussed *when* life arose on Earth, but *how* did it arise? To answer this question, we must first consider how life today differs from the earliest life on Earth. Then we can discuss how the first organisms may have originated.

The Theory of Evolution The fossil record clearly shows that life has gone through great changes over time. If we are going to understand how life arose, we must understand what causes these changes, so that we can trace life back to its origin. The unifying theory through which scientists understand the history of life on Earth is the **theory of evolution**, first published by Charles Darwin in 1859.

The fossil record shows us how life has changed through time, and the theory of evolution explains how these changes have occurred.

Evolution simply means "change with time." Even before Darwin, numerous scientists (some going back to ancient times) had recognized evidence for evolution in the fossil record, but no one before Darwin successfully explained how species might undergo change. In essence, the fossil record provides strong evidence that evolution *has* occurred, while Darwin's theory of evolution explains *how* it occurs.

Darwin's theory tells us that evolution proceeds through a process called **natural selection**. The many individuals of any species always differ in certain small ways. If an individual possesses a trait that gives it an advantage in survival and reproduction, then the trait is likely to be passed on to future generations. We say that nature "selects" the advantageous trait, which is why the process is called natural selection. Over time, natural selection can help individuals of a species become better able to compete for scarce resources. If enough small individual variations accumulate, natural selection can even give rise to an entirely new species.

Darwin compiled a tremendous body of evidence supporting the idea that natural selection is the primary mechanism by which evolution proceeds. Some 150 years of ongoing research has only given further support to Darwin's idea, which is why we call it the *theory* of evolution **[Section 3.4]**. Perhaps the strongest support for the theory has come from the discovery of DNA, the genetic material of all life on Earth. DNA (short for *deoxyribonucleic acid*) has allowed scientists to understand how evolution occurs on a molecular level. Living organisms reproduce by copying DNA and passing these copies on to their descendants. A molecule of DNA consists of two long strands—somewhat like the interlocking strands of a zipper—wound together in the spiral shape known as a double helix (Figure 18.5). The instructions for assembling a living organism are written in the precise order of four chemical bases that make up the interlocking portions of the DNA "zipper." (The four chemical bases are represented in Figure 18.5 by the letters A, T, G, and C, which stand for the first letters of their chemical names.) These bases pair up in a way that ensures that both strands of a DNA molecule contain the same genetic information. By unwinding and allowing new strands (made from chemicals floating around inside a cell) to form alongside the original ones, a single DNA molecule can give rise to two identical copies of itself. That is how genetic material is copied and passed on to future generations.

Evolution occurs because the transfer of genetic information from one generation to the next is not always perfect. An organism's DNA may be occasionally altered by copying errors or by external influences, such as ultraviolet light from the Sun or exposure to toxic or radioactive chemicals. Any change in an organism's DNA is called a **mutation**. Many mutations are lethal, killing the cell in which the mutation occurs. Some, however, may improve a cell's ability to survive and reproduce. The cell then passes on this improvement to its offspring.

Figure 18.5

This diagram represents a small piece of a DNA molecule, which looks like a zipper twisted into a spiral. Hereditary information is contained in the "teeth" linking the strands. These "teeth" are the DNA bases. Only four DNA bases are used, and they can link up between the two strands only in specific ways: T attaches only to A, and C attaches only to G. (The color coding is arbitrary and is used only to represent different types of chemical groups; in the backbone, blue and yellow represent sugar and phosphate groups, respectively.)

Figure 18.6

The tree of life, showing evolutionary relationships determined by comparison of DNA sequences in different organisms. Just two small branches represent *all* plant and animal species.

Our understanding of how natural selection works has put the theory of evolution on a stronger foundation than ever. While no theory can ever be proved true beyond all doubt, the theory of evolution is as solid as any theory in science, including the theory of gravity and the theory of atoms. Biologists routinely witness evolution occurring before their eyes among laboratory microorganisms, or over periods of just a few decades among plants and animals subjected to environmental stress. Moreover, the theory of evolution has become the underpinning of virtually all modern biology, medicine, and agriculture. For example, agricultural scientists apply the idea of natural selection to develop pest control strategies that reduce the populations of harmful insects without harming the populations of beneficial ones; medical researchers test new drugs on animals that are genetically similar to humans, because the theory of evolution tells us that genetically similar species should have somewhat similar physiological responses; and biologists study the genetic relationships between organisms by comparing their DNA.

The First Living Organisms

The basic chemical nature of DNA is virtually identical among all living organisms. This fact, along with other biochemical similarities shared by all living organisms, tells us that all life on Earth today can trace its origins to a common ancestor that lived long ago.

All living organisms today evolved from a common ancestor that lived long ago.

What did the first living organisms look like? We are unlikely to find fossils of the earliest organisms, but we can learn about early life through careful studies of the DNA of living organisms. Biologists can determine the evolutionary relationships among living species by comparing the sequences of bases in their DNA. For example, two organisms whose DNA sequences differ in five places for a particular gene are probably more distantly related than two organisms whose gene sequences differ in only one place. Many such DNA comparisons suggest that all living organisms are related in a way depicted schematically by the "tree of life" in Figure 18.6. Although details in the structure of this tree remain uncertain (particularly because we now know that different species can swap genes), it indicates that life on Earth is divided into three major groupings, or *domains,* called *bacteria*, *archaea*, and *eukarya*, and that all three domains share a common ancestor. Notice that plants and animals represent only two tiny branches of the diverse tree of life.

Organisms on branches located closer to the root of the tree of life must contain DNA that is evolutionarily older, suggesting that they more closely resemble the organisms that lived early in Earth's history. Some of the modern-day organisms that appear to be evolutionarily oldest are microbes that live in very hot water around seafloor volcanic vents called *black smokers* (because of the dark, mineral-rich water that flows out of them) in the deep oceans (Figure 18.7). Unlike most life at Earth's surface, which depends on sunlight, these organisms get energy from chemical reactions in water heated by undersea volcanoes.

Figure 18.7

This photograph shows a black smoker—a volcanic vent on the ocean floor that spews out hot, mineral-rich water. DNA studies indicate that the microbes living near these vents are evolutionarily older than most other living organisms, hinting that early life may have arisen in similar environments.

Early organisms probably arose near a source of chemical energy, such as deep-sea volcanic vents.

The idea that early organisms might have lived in such "extreme" conditions may seem surprising, but it makes sense when we think about it. The deep ocean environment would have been protected from the effects of impacts and from harmful ultraviolet radiation that bathed Earth's

surface before our atmosphere had oxygen or an ozone layer. Moreover, the chemical pathways used to extract energy from mineral-rich hot water are simpler than other chemical pathways (such as photosynthesis) used by living organisms to obtain energy. For these reasons, many scientists suspect that life arose near deep-sea vents, or in similar environments that provided chemical energy.

The Transition from Chemistry to Biology The theory of evolution explains how the earliest organisms evolved into the great diversity of life on Earth today. But where did the first organisms come from? We may never know for sure, because we are unlikely to find fossils that would show the transition from nonlife to life. However, over the past several decades, scientists have conducted laboratory experiments designed to mimic the conditions that existed on the young Earth. These experiments suggest that life could have arisen through natural chemical reactions.

The first such experiments were performed in the 1950s (Figure 18.8), and they have been refined and improved since that time. In essence, the experiments mix chemicals thought to have been present on the early Earth and then "spark" the chemicals with electricity to simulate lightning or other energy sources. The chemical reactions that follow have produced nearly all the major molecules of life, including amino acids and DNA bases. Many of these molecules are also found in meteorites, suggesting that some organic molecules may have arrived from space.

Figure 18.8

Stanley Miller poses with a reproduction of the experimental setup he first used in the 1950s to study pathways to the origin of life. (He worked with Harold Urey, so the experiment is called the Miller-Urey experiment.)

specialTopic | What Is Life?

You may have noticed that while we've been talking about life, we haven't actually defined the term. It's surprisingly difficult to draw a clear boundary between life and nonlife. Life can be so difficult to define that we may be tempted to fall back on the famous words of Supreme Court Justice Potter Stewart, who, in avoiding the difficulty of defining pornography, wrote: "I shall not today attempt further to define [it] . . . . But I know it when I see it." If living organisms on other worlds turn out to be much like those found on Earth, it may prove true that we'll know them when we see them. But if the organisms are fairly different from those on Earth, we'll need clearer guidelines to decide whether they are truly "living."

One approach seeks to identify distinguishing features common to all known life. For example, nearly all living organisms on Earth appear to share the following six key properties:

1. *Order:* Living organisms are not random collections of molecules but rather have molecules arranged in orderly patterns that form cell structures.
2. *Reproduction:* Living organisms are capable of reproducing.
3. *Growth and development:* Living organisms grow and develop in patterns determined at least in part by heredity.
4. *Energy utilization:* Living organisms use energy to fuel their many activities.
5. *Response to the environment:* Living organisms actively respond to changes in their surroundings. For example, organisms may alter their chemistry or movements in the presence of a food source.
6. *Evolutionary adaptation:* Life evolves through natural selection, as organisms pass on traits that make them better adapted to survival in their local environments.

These six properties are all important, but biologists today regard evolution as the most fundamental and unifying of them. Evolutionary adaptation is the only property that can explain the great diversity of life on Earth. Moreover, understanding how evolution works allows us to understand how all the other properties came to be. A simple definition of *life* might therefore be "something that can reproduce and evolve through natural selection."

This definition of life probably suffices for most practical purposes, but some cases may still challenge it. For example, computer scientists have written programs (that is, lines of computer code) that can reproduce themselves (that is, create additional sets of identical lines of code). By adding to the programs instructions that allow random changes, they can even make "artificial life" that evolves on a computer. Should this "artificial life," which consists of nothing but electronic signals processed by computer chips, be considered alive?

The fact that we have such difficulty distinguishing the living from the nonliving on Earth suggests that we should be very cautious about constraining our search for life elsewhere. No matter what definition of life we choose, there's always the possibility that we'll someday encounter something that challenges it. Nevertheless, the properties of reproduction and evolution seem likely to be shared by most if not all life in the universe, and therefore provide a useful starting point as we consider how to explore the possibility of extraterrestrial life.

Figure 18.9

This microscopic photo made with the aid of fluorescent dyes shows short strands of RNA (red) contained within an enclosed membrane (green circle), both of which formed spontaneously with the aid of clay minerals beneath them.

Laboratory studies of the possible origins of life have advanced greatly in the past few years. Scientists have found that naturally occurring clays, which should have been abundant in the early oceans, can catalyze the formation of short strands of RNA, a molecule much like a single strand of DNA. Some of these short RNA molecules can in turn catalyze other reactions. Because some RNA molecules (though not those so far produced in the laboratory) are capable of self-replication, many biologists now presume that RNA was the original genetic material of life on Earth, with DNA coming later.

Laboratory experiments show that the molecules of life form easily under conditions that existed early on Earth.

Equally significantly, experiments have also shown that microscopic enclosed membranes can form on the surfaces of the same clay minerals that help assemble RNA molecules, sometimes with RNA inside them (Figure 18.9). Self-replicating RNA molecules enclosed in such membranes would have in essence made "pre-cells" in which the RNA might have undergone rapid changes. Pre-cells in which RNA replicated faster and more accurately were more likely to spread, leading to a type of positive feedback that would have encouraged even faster and more accurate replication. Given millions of years of chemical reactions occurring all over Earth, it seems plausible that RNA-based life would have arisen first, then eventually evolved into DNA-based life.

Figure 18.10 summarizes the steps by which chemical processes might have led to life on Earth. We may never know whether life really arose in this way, but it seems possible.

Could Life Have Migrated to Earth? Our scenario suggests that life could have arisen naturally here on Earth. However, an alternative possibility is that life arose somewhere else first—perhaps on Venus or Mars—and then migrated to Earth on meteorites. Remember that we have collected meteorites that were blasted by impacts from the surfaces of the Moon and Mars **[Section 9.1]**. Calculations suggest that Venus, Earth, and Mars all should have exchanged many tons of rock, especially in the early days of the solar system when impacts were more common.

The idea that life could travel through space to Earth once seemed outlandish. After all, it's hard to imagine a more forbidding environment than that of space, with no air, no water, and constant bombardment by dangerous radiation from the Sun and stars. However, the presence of organic molecules in meteorites and comets tells us that the building blocks of life can survive in space, and tests have shown that some microbes can survive in space for years.

In a sense, Earth, Venus, and Mars have been "sneezing" on each other for billions of years. Life could conceivably have originated on any

Figure 18.10

A summary of the steps by which chemistry early on Earth may have led to the origin of life.

of these three planets and been transported to the others. It's an intriguing thought, but it does not change our basic scenario for the origin of life—it simply moves it from one planet to another.

A Brief History of Life on Earth Earth formed about $4\frac{1}{2}$ billion years ago, and the giant impact thought to have formed the Moon **[Section 6.4]** probably happened soon after. Mineral evidence suggests that Earth had oceans by 4.3 to 4.4 billion years ago, and those early oceans would have been natural laboratories for chemical reactions that could have led to life. Once life formed, evolution rapidly diversified it.

Despite the rapid pace of evolution, the most complex organisms remained single-celled for at least a billion years after life first arose. All of these organisms probably lived in the oceans, because the lack of a protective ozone layer made the land inhospitable. Things began to change only when oxygen started building up in Earth's atmosphere.

Nearly all the oxygen in our atmosphere was originally released through photosynthesis by single-celled organisms known as *cyanobacteria* (Figure 18.11). These microbes were probably producing oxygen through photosynthesis about 2.5 billion years ago, and possibly much earlier. However, oxygen did not immediately begin to accumulate in the atmosphere. For hundreds of millions of years, chemical reactions with surface rocks pulled oxygen back out of the atmosphere nearly as fast as the cyanobacteria could produce it. But these tiny organisms were abundant and persistent, and eventually the surface rock was so saturated with oxygen that the rate of oxygen removal slowed down. Oxygen then began to accumulate in the atmosphere, though it may not have reached a level that we could have breathed until just a few hundred million years ago.

Today, we often think of oxygen as a necessity for life. However, oxygen was probably poisonous to most organisms living before about 2 billion years ago (and remains a poison to many microbes still living today). The rise of atmospheric oxygen therefore caused tremendous evolutionary pressure, and may have been a major factor in the evolution of complex plants and animals.

There were undoubtedly many crucial changes as primitive microbes gradually evolved into multicellular organisms and early plants and animals, but the fossil record does not allow us to pinpoint the times at which all these changes occurred. However, we see a dramatic change in the fossil record during the *Cambrian period,* 542 million to 500 million years ago (see Figure 18.3). During this period, animal life evolved from tiny and primitive organisms into all the basic body types (phyla) that we find on Earth today. This remarkable diversification occurred in such a short time relative to Earth's history that it is often called the *Cambrian explosion.*

Living organisms remained single-celled for most of Earth's history, with larger plants and animals arising only in the past few hundred million years.

Early dinosaurs and mammals arose some 225 to 250 million years ago, but dinosaurs at first proved more successful and dominated for well over 100 million years. Their sudden demise 65 million years ago **[Section 9.4]** paved the way for the evolution of large mammals—including humans. The earliest humans appeared on the scene only a few million years ago, or after 99.9% of Earth's history to date had already occurred. Our few centuries of industry and technology have come after 99.99999% of Earth's history.

Figure 18.11

This photo shows microscopic chains of modern cyanobacteria. The ancestors of these living organisms produced essentially all the oxygen in Earth's atmosphere.

• What are the necessities of life?

If we are going to look for other worlds that might harbor life, the first step is to understand the necessities of life. While it is possible that life on other worlds could be quite different from life on Earth, it's easiest to begin the search for life by looking for conditions in which organisms from Earth could live. So what exactly does Earth life need to survive?

If we think about ourselves, the requirements for life seem fairly stringent: We need abundant oxygen in an atmosphere that is otherwise not poisonous, we need temperatures in a fairly narrow range of conditions, and we need abundant and varied food sources. However, the discovery of life in "extreme" environments—such as in the hot water near black smokers—shows that many microbes (often called *extremophiles*) can survive in a much wider range of conditions.

Organisms living in hot water prove that at least some microbes can survive in much higher temperatures than we would have guessed. Other organisms live in other extremes. In the freezing cold but very dry valleys of Antarctica, scientists have found microbes that live *inside* rocks, surviving on tiny droplets of liquid water and energy from sunlight. Microscopic life has also been found deep underground in water that fills pores within subterranean rock. We have found life thriving in environments so acidic, alkaline, or salty that humans would be poisoned almost instantly. We have even found microbes that can survive high doses of radiation, making it possible for them to survive for many years in the radiation-filled environment of space.

If we compare all the different forms of life on Earth, we find that life as a whole has only three basic requirements:

- A source of nutrients (atoms and molecules) from which to build living cells
- Energy to fuel the activities of life, whether from sunlight, from chemical reactions, or from the heat of Earth itself
- Liquid water

These requirements give us a basic road map for the search for life elsewhere. If we want to find life on other worlds, it makes sense to start by searching for worlds that offer these basic necessities.

Life on Earth requires nutrients, energy, and liquid water. Of the three requirements, liquid water is the only one that is not common on other worlds.

Interestingly, only the third requirement (liquid water) seems to pose much of a constraint. Organic molecules are present almost everywhere—even on meteorites and comets. Many worlds are large enough to retain internal heat that could provide energy for life, and virtually all worlds have sunlight (or starlight) bathing their surfaces, although the inverse square law for light **[Section 11.1]** means that light provides less energy to worlds farther from their star. Nutrients and energy should therefore be available to some degree on almost every planet and moon. In contrast, liquid water is relatively rare; therefore, the search for liquid water drives the search for life in our universe.

18.2 Life in the Solar System

If we assume that life elsewhere would be at least a little bit like life on Earth, then the search for life begins with a search for **habitable worlds**—worlds that contain the basic necessities for life as we know it,

including liquid water. The liquid water requirement rules out most of the worlds in our solar system. Mercury and the Moon are barren and dry, Venus is too hot for liquid water, and most of the small bodies of the outer solar system are too cold. The jovian planets may have droplets of liquid water in some of their clouds, but the strong vertical winds on these planets make them unlikely homes for life. That leaves two major possibilities besides Earth for habitability in our solar system: (1) Mars and (2) a few of the large moons orbiting jovian planets, most notably Europa **[Section 8.2]**. Let's discuss the current evidence about the potential habitability of these worlds.

think about it Is it possible for a world to be habitable but not actually have life? Is it possible for a world to have life but not be habitable? Explain.

• Could there be life on Mars?

We now have sufficiently detailed images of Mars to be quite confident that no civilizations have ever existed there. The canals seen by Percival Lowell were some type of mirage, presumably formed by a combination of real Martian features and his own imagination. Nevertheless, we have good reason to believe that liquid water flowed on Mars in the past **[Section 7.3]**, making it seem possible that life could once have found a home there. Moreover, since Mars contains subsurface ice today, it's conceivable that life could still survive near sources of volcanic heat, where pockets of liquid water might persist underground.

Missions to Mars Mars is not only the best candidate in our solar system for life beyond Earth, but also the only place where we've begun an actual search for life. The *Viking* missions to Mars in the 1970s were our first attempt. Two landers arrived on the surface of Mars in 1976. Each was equipped with a robotic arm for scooping up soil samples, which were fed into several on-board, robotically controlled experiments.

Three of the *Viking* experiments were designed to look for chemical changes in the soil samples that could be attributed to living organisms. Although all three experiments gave results that initially seemed consistent with life, further study suggested that chemical reactions could have produced the same results. A fourth experiment, which analyzed the content of Martian soil, found no measurable level of organic molecules—the opposite of what we would expect if life were present. The significance of this result is still being debated, but most scientists doubt that life was present in the *Viking* soil samples.

Mars may have been habitable in the past and could have underground liquid water today, making it a prime target for space missions searching for life.

Recent missions have taken a more measured approach to the search for life on Mars (Figure 18.12). Rather than conducting direct experiments like *Viking*, these missions have been designed to help us better understand Martian conditions, so that we'll have a better idea of how and where to search for life with future missions.

Figure 18.12

The *Spirit* rover studies a rock on Mars (the photograph was taken by a camera aboard the rover). Such studies help scientists learn if and when Mars may have been habitable.

Methane on Mars Atmospheric studies can also provide clues about potential life, and scientists are particularly intrigued by the recent detection of methane (CH_4) in the Martian atmosphere. Atmospheric methane is quickly destroyed by ultraviolet light from the Sun, so its presence

means that it is being continually released from the Martian surface. Moreover, the amount of methane in the atmosphere appears to vary regionally across Mars, and also seems to vary with the Martian seasons. Could it be that the methane is being produced by life, as is the case for most of the methane in Earth's atmosphere?

It's certainly possible, but methane can also be produced by nonbiological processes. For example, volcanoes release methane, so low levels of volcanic activity could be responsible for the methane on Mars, and the seasonal variations may be due to escape routes for gas from underground being plugged in the winter and clear in the summer. However, even if the source is volcanic rather than biological, the methane may be significant to the possibility of life. The amount of volcanic heat necessary for methane release would probably also be sufficient to maintain pockets of liquid water underground, which could potentially provide a habitat for life.

Scientists hope to learn more by analyzing the methane distribution more carefully, by studying methane release sites, and by learning the precise isotopic makeup of the gas. The *Mars Science Laboratory*, scheduled for launch in October 2011, may be able to investigate the source of the methane.

think about it Find the current status of the *Mars Science Laboratory*. If it has reached Mars by the time you read this book, has it found anything of significance to the search for life?

The Debate over Martian Meteorites An entirely different approach to the search for life on Mars relies on studies of meteorites whose chemical composition suggests they came from Mars. One of these meteorites, designated ALH84001, generated particular excitement when a group of scientists claimed that it contained evidence of past life on Mars (Figure 18.13).

ALH84001 was found on the Antarctic ice in 1984. Careful study of the meteorite shows that it landed in Antarctica about 13,000 years ago, following a 16-million-year journey through space after being blasted from Mars by an impact. The rock itself dates to about 4.1 billion years ago, which means that it resided on Mars during times when the climate may have been warmer and wetter. Analysis of the meteorite reveals several lines of evidence that could indicate the past presence of life on Mars. For example, the rock contains layered carbonate minerals and complex organic molecules (polycyclic aromatic hydrocarbons, or PAHs) that are associated with life when found in Earth rock, as well as microscopic

a The Martian meteorite ALH84001, before it was cut open for detailed study. The block on the right provides a sense of scale; it measures 1 cubic centimeter, about the size of a typical sugar cube.

b The tiny rod-shaped structures in this microscopic photo (of a slice of ALH84001) look much like fossilized bacteria, except they are smaller.

Figure 18.13

Controversial meteorite evidence for life on Mars.

chains of magnetite crystals quite similar to chains made in Earth rocks by living bacteria. Most intriguingly, highly magnified images reveal rod-shaped structures that look much like ordinary bacteria, except that they are much smaller. Could these structures be fossil life from Mars?

A meteorite from Mars shows tantalizing evidence of past life, but the evidence can also be explained in a nonbiological way.

It's possible, but each of the tantalizing hints of Martian life can also be explained in a nonbiological way. Subsequent studies have shown that chemical and geological processes can produce structures very similar to those found in the Martian meteorite. In addition, terrestrial bacteria have been found living inside the meteorite, indicating that it was contaminated by Earth life during the 13,000 years it resided in Antarctica. This contamination may explain the presence of the complex molecules found in the rock. Overall, most scientists now doubt that the Martian meteorite shows true evidence of Martian life. Nevertheless, studies of ALH84001 and other Martian meteorites are continuing, and they may yet turn up surprises.

• Could there be life on Europa or other jovian moons?

After Mars, the next most likely candidates for life in our solar system are some of the moons of the jovian planets—especially Jupiter's moons Europa, Ganymede, and Callisto and Saturn's moons Titan and Enceladus **[Section 8.2]**. Europa is the strongest candidate, because we have good reason to think it contains a deep ocean beneath its icy crust (see Figure 8.17). The ice and rock from which Europa formed undoubtedly included the necessary chemical ingredients for life, and Europa's internal heating (primarily due to tidal heating) is strong enough to power volcanic vents on its seafloor. If life on Earth arose near such undersea volcanic vents, Europa would seem to have everything needed for life to originate.

If Europa's ocean really exists, it may have seafloor vents much like those in Earth's oceans, where early life may have thrived.

The possibility of life on Europa is especially interesting because, unlike any potential life on Mars, it would not necessarily have to be microscopic. After all, the several kilometers of surface ice that hide Europa's suspected ocean could also hide large creatures swimming within it. However, the potential energy sources for life on Europa are far more limited than the energy sources for life on Earth (mainly because sunlight could not fuel photosynthesis in the subsurface ocean). As a result, most scientists suspect that any life that might exist on Europa would probably be quite small and primitive.

As we discussed in Chapter 8, some evidence suggests that Jupiter's moons Ganymede and Callisto may also have subsurface oceans. However, these moons would have even less energy for life than Europa. If they have life at all, it is almost certainly small and primitive. Nevertheless, Europa, Ganymede, and Callisto offer the astonishing possibility that Jupiter alone could be orbited by more worlds with life than we find in all the rest of the solar system.

Titan offers another enticing place to look for life. Its surface is far too cold for liquid water, but it has lakes and rivers of liquid methane and ethane **[Section 8.2]**. Although many biologists think it unlikely, it is possible that this liquid could support life as water does on Earth. Titan might also have liquid water or a colder ammonia–water mixture deep underground, so even water-based life might exist, though the chances are slim.

The discovery of ice fountains on Saturn's moon Enceladus suggests that it, too, could be habitable if these fountains are powered by subsurface liquids. If this proves to be the case, it would open up the possibility that similar liquids—and potentially life—could exist on other solar system bodies, including Neptune's moon Triton and some of the moons of Uranus.

Other possible homes to life in our solar system include Jupiter's moons Ganymede and Callisto and Saturn's moons Titan and Enceladus.

MA Detecting Extrasolar Planets Tutorial, Lessons 1–3

18.3 Life Around Other Stars

Studies of extrasolar planets **[Section 6.5]** suggest that our galaxy contains billions of planetary systems, so the prospects for life elsewhere might seem quite good. But numbers alone don't tell the whole story. In this section, we'll consider the prospects for life on worlds orbiting other stars.

Before we begin, we must distinguish between *surface* life like that on Earth and *subsurface* life like that we envision as a possibility on Mars or Europa. While large telescopes could in principle allow us to discover surface life on extrasolar planets, no foreseeable technology will allow us to find life that is hidden deep underground in other star systems (unless the subsurface life has a noticeable effect on the planet's atmosphere). We therefore will focus on the search for life on planets with habitable surfaces—surfaces with temperatures and pressures that could allow liquid water to exist.

• Are habitable planets likely?

As we discussed in Chapter 6, our technology is just reaching the point where we can detect extrasolar planets similar in size to Earth in orbits that could make them habitable. However, even before we have found many such planets, we can address the questions of where we might expect them to exist and whether they are likely to be habitable.

Constraints on Star Systems Before we consider planets themselves, it's useful to ask how many stars could potentially have planets with life. In other words, which stars would make good "suns," providing heat and light to the surfaces of terrestrial planets that happen to orbit them?

The first constraint concerns stellar lifetimes. The example of Earth suggests that life may not take hold for up to a few hundred million years after a planet first forms, so we would expect to find life only around stars with lifetimes of hundreds of millions of years or more. This constraint rules out stars with more than a few times the mass of our Sun, because these stars have short lifetimes **[Section 12.3]**. However, because low-mass stars are far more common than high-mass stars, the lifetime constraint rules out only about 1% of all stars.

A second constraint is that the star must allow planets to have stable orbits. About half of all stars are in binary or multiple star systems, around which stable planetary orbits are less likely than around single stars. If life were not possible in such systems, then we would rule out about half the stars in our galaxy as potential homes to life. Of course, the other half—which still means 100 billion or more stars—would remain possible homes for life. Moreover, under some circumstances, stable planetary orbits are

Figure 18.14 MA interactive figure

The approximate habitable zones around our Sun, a star with one half the mass of our Sun (spectral type K), and a star with one tenth the mass of our Sun (spectral type M), shown to scale. The habitable zone becomes increasingly smaller and closer in for stars of lower mass and luminosity.

possible in multiple star systems, and planets in such systems have already been found. So it now seems that we can't rule out life in binary systems, though some may be unsuitable.

A third constraint is the size of a star's **habitable zone**—the region in which a terrestrial planet of the right size could have a surface temperature that might allow for liquid water and life. Figure 18.14 shows the approximate sizes, to scale, of the habitable zones around our Sun, around a star with about one half the mass of our Sun (spectral type K), and around a star with about one tenth the mass of our Sun (spectral type M). Although habitable planets seem possible in all three cases, the smaller size of the habitable zones around the less massive stars may make it less likely that suitable planets would have formed in these regions.

Although not all star systems are potential homes for life, many billions of stars in our galaxy could be orbited by habitable planets.

All in all, it seems that the vast majority of stars are at least potentially capable of having life-bearing planets. Even very conservative assumptions suggest enormous numbers of possibilities. For example, limiting the search for habitable planets to stars similar to our Sun (that is, spectral type G) would still mean billions of potential suns in the Milky Way Galaxy.

Finding Habitable Planets Finding Earth-size planets is a daunting technological challenge **[Section 6.5]**. Recall that looking for an Earth-like planet around a nearby star is like standing on the East Coast of the United States and looking for a pinhead on the West Coast. Nevertheless, efforts to find such planets are already under way. Scientists are optimistic that the *Kepler* mission **[Section 6.5]**, launched in 2009, will detect dozens of Earth-size planets and tell us whether these planets lie within their stars' habitable zones.

We will need images or spectra to determine whether the planets really are habitable or have life. Scientists are actively working on technologies that may provide such data. Within the next couple of decades, NASA hopes to launch an orbiting telescope that will be capable of obtaining low-resolution spectra and crude images (a few pixels) of Earth-like planets around nearby stars.

Signatures of Life Images from future telescopes may tell us whether extrasolar planets have continents and oceans like Earth and perhaps even allow us to monitor seasonal changes. Spectra should prove even more important to the search for life. Moderate-resolution infrared spectra can reveal the presence and abundance of many atmospheric

Figure 18.15

The infrared spectra of Venus, Earth, and Mars, as they might be seen from afar, showing absorption features that point to the presence of carbon dioxide (CO_2), ozone (O_3), and sulfuric acid (H_2SO_4) in their atmospheres. While carbon dioxide is present in all three spectra, only our own planet has appreciable oxygen (and hence ozone)—a product of photosynthesis. If we could make similar spectral analyses of distant planets, we might detect atmospheric gases that would indicate life.

Figure 18.16

The highlighted green ring in this painting of the Milky Way Galaxy represents what some scientists suspect to be a galactic habitable zone—the only region of the galaxy in which Earth-like planets are likely to be found. However, other scientists think that Earth-like planets could be far more widespread.

gases, including carbon dioxide, ozone, methane, and water vapor (Figure 18.15). Careful analysis of atmospheric makeup might tell us whether a planet has life.

Future telescopes may be capable of obtaining images and spectra that will tell us whether distant terrestrial worlds are habitable or have life.

On Earth, for example, the large abundance of oxygen (21% of our atmosphere) is a direct result of photosynthetic life. Abundant oxygen in the atmosphere of a distant world might similarly indicate the presence of life, since we know of no nonbiological way to produce an oxygen abundance as high as Earth's. Other evidence might come from the ratio of oxygen to the other detected gases. Scientists are working to improve our understanding of how life influences atmospheric chemistry, in the hope that we will be able to recognize particular gas combinations as signatures of life.

• Are Earth-like planets rare or common?

We will not know for certain whether habitable planets exist or how common they may be until we survey many star systems with telescopes capable of detecting such small planets. Nevertheless, the existence of more than one Earth-size planet in our own solar system and our understanding of planetary formation make it seem reasonable to think that many Earth-size planets exist within the habitable zones of other stars. But should we expect these planets to have Earth-like conditions in which life could arise and evolve?

Most scientists think so, but a few have raised some interesting questions. In essence, these scientists suggest that Earth's hospitable environment is the result of several rare kinds of planetary luck. According to this idea, sometimes called the "rare Earth hypothesis," the specific circumstances that have allowed life on Earth to survive and evolve into complex forms (such as oak trees and people) might be so rare that ours could be the only planet in the galaxy that harbors anything but the simplest life. Let's briefly examine some of the key issues in the rare Earth hypothesis.

Galactic Constraints Proponents of the rare Earth hypothesis suggest that Earth-like planets can form in only a relatively small region of the Milky Way Galaxy, making the number of potential homes for life far smaller than we might otherwise expect it to be. In essence, they argue that there is a fairly narrow ring at about our solar system's distance from the center of the Milky Way Galaxy that makes up a *galactic habitable zone* analogous to the habitable zone around an individual star (Figure 18.16).

According to the arguments for a galactic habitable zone, outer regions of our galaxy are unlikely to have terrestrial planets because of a low abundance of elements other than hydrogen and helium. Recall that the fraction of heavy elements varies among stars, from less than 0.1% among the old stars in globular clusters to more than 2% among young stars in the galactic disk **[Section 14.3]**. Even within the galactic disk, the abundance tends to decline with distance from the center of the galaxy. Because terrestrial planets are made almost entirely of heavy elements, a lower abundance of these elements might lessen the chance that terrestrial planets could form. The inner regions of the galaxy are ruled out primarily through an argument concerning supernova rates. Supernovae are more common in the more crowded, inner regions of the galactic disk, making it more likely that a terrestrial planet would be exposed to the intense radiation from a nearby supernova. By assuming that this radiation would be detrimental to life, the proponents of a

galactic habitable zone argue against finding habitable planets in the inner regions of the galaxy. Together, the constraints on finding Earth-like planets in the inner and outer regions of the galaxy leave the galactic habitable zone as a relatively narrow ring encompassing no more than about 10% of the stars in the galactic disk.

However, other scientists offer counterarguments to both sets of galactic constraints. Although discoveries of extrasolar planets to date suggest that *large* planets are indeed rarer around stars with very low fractions of heavy elements, we cannot yet say whether terrestrial planets are rare in such systems. Remember that Earth's mass is less than $\frac{1}{100,000}$ of the mass of the Sun, so even a very small heavy-element abundance could be enough to make one or more Earth-like planets. Regarding the radiation danger from supernovae, we do not really know whether such radiation would be detrimental to life. A planet's atmosphere might protect life against the effects of this radiation. It is even possible that the radiation could be beneficial to life by increasing the rate of mutations and thereby accelerating the pace of evolution. If these counterarguments are correct, then Earth-like planets might be found throughout much or all of the galaxy.

Impact Rates and Jupiter Another issue raised by rare Earth proponents is the impact rate on planets in other star systems. Earth was probably subjected to numerous large impacts—some large enough to vaporize the oceans—during the heavy bombardment that went on during the first half-billion years or so after our planet's birth. In our solar system, the impact rate lessened dramatically after that. But could the impact rate remain high much longer in other planetary systems?

The most numerous small objects in our solar system are the trillion or so comets of the distant Oort cloud **[Section 9.2]**. Fortunately for us, nearly all these myriad objects are essentially out of reach, posing no threat to our planet. However, the reason they are out of reach can be traced directly to Jupiter: Recall that the Oort cloud's comets are thought to have formed among the jovian planets, later being "kicked out" to their current orbits by close encounters with these planets, especially Jupiter (see Figure 9.25). If Jupiter did not exist, many of these comets might have remained in regions of the solar system where they could pose a danger to Earth. In that case, the heavy bombardment might never have ended, and huge impacts would continue to this day. From this viewpoint, our existence on Earth has been possible only because of the "luck" of having Jupiter as a planetary neighbor.

The primary question in this case is just how "lucky" this situation might be. Our discoveries of extrasolar planets so far suggest that Jupiter-size planets are quite common. However, we've also found that many large planets migrate inward **[Section 6.5]**, perhaps disrupting terrestrial planet orbits along the way. Whether most star systems have a Jupiter in the right place for ejecting comets remains an open question.

Climate Stability Another issue affecting the rarity of Earth-like planets is climate stability. Earth's climate has been stable enough for liquid water to exist throughout the past 4 billion years. This climate stability has almost certainly played a major role in allowing complex life to evolve. If our planet had frozen over like Mars or overheated like Venus, we would not be here today. Advocates of the rare Earth hypothesis point to at least two pieces of "luck" related to Earth's stable climate.

The first piece of "luck" is the existence of plate tectonics. Recall that plate tectonics is a key part of regulating Earth's climate through the carbon dioxide cycle **[Section 7.5]**. Plate tectonics probably was not necessary to the origin of life, but it seems to have been important in keeping the climate stable enough for the subsequent evolution of plants and animals. But are we really "lucky" to have plate tectonics, or should this geological process be common on similar-size planets elsewhere? We do not yet know. The lack of plate tectonics on Venus, which is quite similar in size to Earth, might seem to argue for plate tectonics being rare. On the other hand, if Venus's lack of plate tectonics is due to its runaway greenhouse effect, as many scientists suspect **[Section 7.4]**, then Venus might have had plate tectonics if it had been born a little farther from the Sun. In that case, it's possible that any Earth-size planet within a star's habitable zone would have plate tectonics.

The second piece of "luck" in climate stability is the existence of Earth's relatively large Moon. Models of Earth's rotation and orbit show that if the Moon did not exist, gravitational tugs from other planets would cause large swings in Earth's axis tilt over periods of tens to hundreds of thousands of years. (Such swings in axis tilt are thought to occur on Mars.) Changes in axis tilt would affect the severity of the seasons, which in turn could cause deeper ice ages and more intense periods of warmth. Given that the Moon formed as a result of a random, giant impact **[Section 6.4]**, we might seem to be very lucky to have the Moon and the climate stability it brings.

Again, there are other ways to look at the issue. First, the expected changes in axis tilt also depend on rotation rate; if Earth rotated in less than about 12 hours, the axis would be fairly stable even without the Moon. Second, the Moon's presumed formation in a random giant impact does not necessarily mean that large moons are rare, because solar system formation models indicate that at least a few giant impacts should be expected in any planetary system. Finally, even if the axis tilt changes dramatically, this may not have a major impact on potential life. Changes in axis tilt might warm or cool different parts of the planet dramatically, but the changes would probably occur slowly enough for life to adapt or migrate as the climate changed.

The Bottom Line The bottom line is that while the rare Earth hypothesis offers some intriguing arguments, it is too early to say whether any of them will hold up over time. For each potential argument that Earth has been lucky, we've seen counterarguments suggesting otherwise. There's no doubt that our solar system and our world have "personality"—they exhibit properties that might be found only occasionally in other star systems—but we have no clear reason to think that these special properties are essential to the existence of complex or even intelligent life.

The rare Earth hypothesis suggests that Earth has been the beneficiary of several instances of rare planetary luck, but it remains controversial.

Indeed, it may be that we have missed out on some helpful phenomena that could have sped evolution on Earth. We might be less lucky than we recognize, and creatures on other worlds might regard the nature of our planet with disappointment. Until we learn more about other planets in the universe, we cannot know whether Earth-like planets and complex life are common or rare.

18.4 The Search for Extraterrestrial Intelligence

So far, we have focused on search strategies for microbial or other non-intelligent life. However, if intelligent beings and civilizations exist elsewhere, we might be able to find them with a completely different type of strategy. Instead of searching for hard-to-find spectroscopic signs of life, we might simply listen for signals that intelligent beings are sending into interstellar space, either in deliberate attempts to contact other civilizations or as a means of communicating among themselves. The search for signals from other civilizations is generally known as the **search for extraterrestrial intelligence**, or **SETI** for short.

• How many civilizations are out there?

SETI efforts have a chance to succeed only if other advanced civilizations are broadcasting signals that we could receive. To judge the chances of SETI success, we'd need to know how many civilizations are broadcasting such signals right now.

Given that we do not even know whether microbial life exists anywhere beyond Earth, we certainly don't know whether other civilizations exist, let alone how many there might be. Nevertheless, for the purposes of planning a search for extraterrestrial intelligence, it is useful to have an organized way of thinking about the number of civilizations that might be out there. To keep our discussion simple, let's consider only the number of potential civilizations in our own galaxy. We can always extend our estimate to the rest of the universe by simply multiplying the result we find for our galaxy by 100 billion, the approximate number of galaxies in our universe.

The Drake Equation In 1961, astronomer Frank Drake wrote a simple equation designed to summarize the factors that would determine the number of civilizations we might contact (Figure 18.17).

The Drake equation summarizes the factors that determine the number of civilizations in our galaxy with which we could potentially communicate.

This equation is now known as the **Drake equation**, and in principle it gives us a simple way to calculate the number of civilizations capable of interstellar communication that are currently sharing the Milky Way Galaxy with us. In a form slightly modified from the original, the Drake equation looks like this:

$$\text{Number of civilizations} = N_{HP} \times f_{life} \times f_{civ} \times f_{now}$$

This equation will make sense once you understand the meaning of each factor:

- N_{HP} is the number of habitable planets in the galaxy—that is, the number of planets that could *potentially* have life.
- f_{life} is the fraction of habitable planets that actually have life. For example, $f_{life} = 1$ would mean that all habitable planets have life, and $f_{life} = \frac{1}{1{,}000{,}000}$ would mean that only 1 in a million habitable planets have life. Thus, the product $N_{HP} \times f_{life}$ tells us the number of life-bearing planets in the galaxy.
- f_{civ} is the fraction of the life-bearing planets upon which a civilization capable of interstellar communication *has at some time* arisen. For example, $f_{civ} = \frac{1}{1000}$ would mean that such a civilization has existed

Figure 18.17

Astronomer Frank Drake, with the equation he first wrote in 1961. (With Dr. Drake's approval, we use a slightly modified form of his equation in this book.)

on 1 out of 1000 planets with life, while the other 999 out of 1000 have not had a species that learned to build radio transmitters, high-powered lasers, or other devices for interstellar conversation. When we multiply this factor by the first two factors to form the product $N_{HP} \times f_{life} \times f_{civ}$, we get the total number of planets upon which intelligent beings have evolved and developed a communicating civilization at some time in the galaxy's history.

- f_{now} is the fraction of these civilization-bearing planets that happen to have a civilization *now,* as opposed to, say, millions or billions of years in the past. This factor is important because we can hope to contact only civilizations that are broadcasting signals we could receive at present (assuming we take into account the light-travel time for signals from other stars). Because the product of the first three factors tells us the total number of civilizations that have *ever* arisen in the galaxy, multiplying by f_{now} tells us how many civilizations we could potentially make contact with today. In other words, the result of the Drake equation is the number of civilizations that we might hope to contact.

We do not know the values of any of the factors in the Drake equation, but it is still a useful tool for organizing our thinking.

Unfortunately, we don't yet know the values of any of the factors in the Drake equation, so we cannot actually calculate the number of civilizations in our galaxy. Nevertheless, the equation is a useful way of organizing our thinking, as we can see by considering the potential values for each of its factors.

think about it Try the following sample numbers in the Drake equation. Suppose that there are 1000 habitable planets in our galaxy, that 1 in 10 habitable planets has life, that 1 in 4 planets with life has at some point had an intelligent civilization, and that 1 in 5 civilizations that have ever existed is in existence now. How many civilizations would exist at present? Explain.

The Number of Life-Bearing Planets Let's begin with the first two factors in the Drake equation, whose product ($N_{HP} \times f_{life}$) tells us the number of life-bearing planets in our galaxy. We can make a reasonably educated guess only about the first factor, the number of habitable planets (N_{HP}). Current understanding of solar system formation (see Figure 6.24) suggests that terrestrial planets ought to form easily and, as discussed earlier, there ought to be billions of stars in our galaxy with habitable zones large enough to have Earth-like planets. Unless some of the "rare Earth" ideas prove to be correct, it seems reasonable to suppose our galaxy has billions of habitable planets.

Our galaxy is likely to have billions of habitable planets, but we have no reliable way to estimate the fraction of them that actually have life.

The factor f_{life} presents more difficulty. At present, we have no reliable way to estimate the fraction of habitable planets upon which life actually arose. The problem is that we cannot generalize when we have only one example to study—our own Earth. Still, the fact that life arose rapidly on Earth suggests that the origin of life was fairly "easy." In that case, we might expect most or all habitable planets to also have life, making the fraction f_{life} close to 1. Of course, until we have solid evidence that life arose anywhere else, such as on Mars, it is also possible that Earth has been very lucky and that f_{life} is so close to zero that life has never arisen on any other planet in our galaxy.

The Question of Intelligence Even if life-bearing planets are very common, civilizations capable of interstellar communication might not be. The fraction of life-bearing planets that at some time have such civilizations, f_{civ}, depends on at least two things: First, a planet would have to have a species evolve with sufficient intelligence to develop interstellar communication. In other words, the planet needs a species at least as smart as we are. Second, that species would have to develop a civilization with technology at least as advanced as ours.

Although we cannot really be sure, most scientists suspect that only the first requirement is difficult to meet. A fundamental assumption in nearly all of science today is that we are not "special" in any particular way. We live on a fairly typical planet orbiting an ordinary star in a normal galaxy, and we assume that living creatures elsewhere—whether they prove to be rare or common—would be subjected to evolutionary pressures similar to those that have operated on Earth. Therefore, if species with intelligence similar to ours have arisen elsewhere, we assume that they would have similar sociological drives that would eventually lead them to develop the technology necessary for interstellar communication.

If this assumption is correct, then the fraction f_{civ} depends primarily on the question of whether sufficient intelligence is rare or common among life-bearing planets. As with the question of life of any kind, the short answer is that we just don't know, but we can get at least some insight by considering what happened on Earth.

Life on Earth arose quickly, but it took nearly 4 billion years to develop a species intelligent enough to learn about it.

Look again at Figure 18.3. While life arose quite quickly on Earth, nearly all life remained microbial until just a few hundred million years ago, and it took nearly 4 billion years for humans to arrive on the scene. This slow progress toward intelligence might suggest that producing a civilization is very difficult even when life is present. On the other hand, roughly half the stars in the Milky Way are older than our Sun, so if Earth's case is typical, then plenty of planets have existed long enough for intelligence to arise.

Another way to address the question is by considering our level of intelligence in comparison to that of other animals on Earth. We can get a rough measure of intelligence by comparing brain mass to total body mass (a measure sometimes called the *encephalization quotient,* or EQ). Figure 18.18 shows the brain weights for a sampling of birds and mammals plotted against their body weights. There is a clear and expected trend in that heavier animals have heavier brains. By drawing a straight line that fits these data, we can define an average value of brain mass for each body mass. Animals whose brain mass falls above the line are smarter than average, while animals whose brain mass falls below the line are less mentally agile. Keep in mind that it is the *vertical* distance above the line that tells us how much smarter a species is than the average, and that the scale goes in powers of 10 on both axes. If you look closely, you'll see that the data point for humans lies significantly farther above the line than the data point for any other species. By this measure of intelligence, we are far smarter than any other species that has ever existed on Earth.

Some people use this fact to argue that even on a planet with complex life, a species as intelligent as we are would be very rare. They say that even if there is an evolutionary drive toward intelligence in general, it takes extreme luck to reach our level of intelligence. After all, while it's evolutionarily useful to have enough intelligence to capture prey and evade other predators, it's not clear why natural selection

Figure 18.18

This graph shows how brain mass compares to body mass for some mammals (including primates) and birds. The straight line represents an average of the ratio of brain mass to body mass, so animals that fall above the line are smarter than average and animals that fall below the line are less smart. Note that the scale uses powers of 10 on both axes. (Data from Harry J. Jerison, 1973.)

would lead to brains big enough to build spacecraft. However, the same data can be used to reach an opposite conclusion. The scatter in the levels of intelligence among different animals tells us that some variation should be expected, and statistical analysis shows that we are not unreasonably far above the average. It might therefore be inevitable that some species would develop our level of intelligence on any planet with complex life.

Technological Lifetimes For the sake of argument, let's assume that life and intelligence are reasonably likely, so thousands or millions of planets in our galaxy have at some time given birth to a civilization. In that case, the final factor in the Drake equation, f_{now}, determines the likelihood of there being someone whom we could contact now. The value of this factor depends on how long civilizations survive.

Consider our own example. In the roughly 12 billion years during which our galaxy has existed, we have been capable of interstellar communication via radio for only about 60 years. If we were to destroy ourselves tomorrow, then other civilizations could have received signals from us during only 60 years out of the galaxy's 12-billion-year existence, equivalent to 1 part in 200 million of the galaxy's history. If such a short technological lifetime is typical of civilizations, then f_{now} would be only $\frac{1}{200{,}000{,}000}$ and some 200 million civilization-bearing planets would need to have existed at one time or another in the Milky Way in order for us to have a decent chance of finding another civilization out there now.

Even if civilizations arise on many planets, they are unlikely to exist today unless they avoid early self-destruction.

However, we'd expect f_{now} to be so small only if we are on the brink of self-destruction—after all, the fraction will grow larger for as long as our civilization survives. Thus, if civilizations are at all common, survivability is the key factor in whether any are out there now. If most civilizations self-destruct shortly after achieving the technology for interstellar communication, then we are almost certainly alone in the galaxy at present. But if most survive and thrive for thousands or millions of years, the Milky Way may be brimming with civilizations—most of them far more advanced than our own.

think about it Describe a few reasons why a civilization capable of interstellar communication would also be capable of self-destruction. Overall, do you believe our civilization can survive for thousands or millions of years? Defend your opinion.

Figure 18.19

The Allen Telescope Array, in Hat Creek, California, is being used to search for radio signals from extraterrestrial civilizations.

• How does SETI work?

If there are indeed other civilizations out there, then in principle we ought to be able to make contact with them. Based on our current understanding of physics, it seems likely that even very advanced civilizations would communicate much as we do—by encoding signals in radio waves or other forms of light. Most SETI researchers use large radio telescopes to search for alien radio signals (Figure 18.19). A few researchers are studying other parts of the electromagnetic spectrum as well. For example, some scientists use visible-light telescopes to search for communications encoded as laser pulses. Of course, advanced civilizations may well have invented communication technologies that we cannot even imagine, let alone detect.

A good way to think about our chances of picking up an alien signal is to imagine what aliens would need to do to pick up signals from us. We have been sending relatively high-power transmissions into space since about the 1950s in the form of television broadcasts. In principle, anyone within about 60 light-years of Earth could watch our old television shows (perhaps a frightening thought). However, in order to detect our broadcasts, they would need far larger and more sensitive radio telescopes than we have today. If their technology were at the same level as ours, they could receive a signal from us only if we deliberately broadcast an unusually high-powered transmission.

In principle, aliens within 60 light-years of Earth could watch past television broadcasts. Our own current SETI efforts could pick up only much stronger signals.

To date, humans have made only a few attempts to broadcast our existence in this way. The most famous was a 3-minute transmission

specialTopic | Are Aliens Already Here?

In this chapter, we have discussed contact with intelligent aliens as a possibility, not a reality. However, public opinion polls suggest that up to half the American public believes that aliens are already visiting us. What can science say about this remarkable notion?

The bulk of the claimed evidence for alien visitation consists of sightings of UFOs—unidentified flying objects. Many thousands of UFOs are reported each year, and no one doubts that unidentified objects are being seen. The question is whether they are alien spacecraft.

Aliens have long been a staple of science fiction, but modern interest in UFOs began with a widely reported sighting in 1947. While flying a private plane near Mount Rainier in Washington State, businessman Kenneth Arnold saw nine mysterious objects streaking across the sky. He told a reporter that the objects "flew erratic, like a saucer if you skip it across the water." (In fact, he may have seen meteors skipping across the atmosphere, though no one knows for sure.) He did not say that the objects were saucer-shaped, but the reporter nevertheless wrote up Arnold's experience as a sighting of "flying saucers." The story was front-page news throughout America, and "flying saucers" soon invaded popular culture, if not our planet.

The flying saucer reports also interested the U.S. Air Force, largely out of concern that the UFOs might represent new types of aircraft developed by the Soviet Union. For two decades, the Air Force hired teams of academics to study UFO reports. In most cases, these experts were able to specify a plausible identification of the UFO. The explanations included bright stars and planets, aircraft, rockets, balloons, birds, meteors, atmospheric phenomena, and the occasional hoax. In a few cases, the investigators could not deduce what was seen, but their overall conclusion was that there was no reason to believe the UFOs were either highly advanced Soviet craft or visitors from other worlds.

Believers discounted the Air Force denials, claiming to have other evidence of alien visitation. So far, none of this evidence has withstood scientific scrutiny. Photographs and film clips are nearly always too fuzzy to clearly show alien spacecraft, except in cases that are obviously faked. UFO witnesses are frequently credible (they include seasoned pilots), but generally there are several possible explanations for what they've seen besides alien spacecraft. Crop circles are easily made by pranksters. Stories of alien abductions are dramatic but cannot be verified. Pieces of metal that "UFO experts" say could not have been made by humans have turned out to be pieces of cars or refrigerators. Champions of alien visitation generally explain away the lack of clear evidence in one of two ways: government cover-ups or a failure of the mainstream scientific community to take the relevant phenomena seriously. Neither explanation is compelling.

It's conceivable that a secretive government might *try* to put the lid on evidence of alien visits, though the motivation for doing so is unclear. The usual explanations are that the public couldn't handle the news or that the government is taking secret advantage of the alien materials to design new military hardware (via "reverse-engineering"). Both explanations are silly. Half the population already believes in alien visitors and would hardly be shocked if newspapers announced that aliens were stacked up in government warehouses. As for reverse-engineering extraterrestrial spacecraft, we should keep in mind how difficult it is to travel from star to star. Any society that could do so routinely would be technologically far beyond our own. Reverse-engineering their spaceships is as unlikely as expecting Neandertals to construct personal computers just because a laptop somehow landed in their cave. In addition, while a government might successfully hide evidence for a short time, over decades the lure of talk show fame and riches would surely cause someone to reveal the conspiracy. Moreover, unless the aliens landed only in the United States, we would have to assume that all governments on Earth were cooperating in hiding the evidence.

Alleged disinterest on the part of the scientific community is an equally unimpressive claim. Scientists are constantly competing with one another to be the first to make a great discovery, and clear evidence of alien visitors would be one of the most important discoveries of all time. Countless researchers would work evenings and weekends, without pay, if they thought they could make such a discovery. The fact that few scientists are engaged in such study reflects not a lack of interest, but a lack of evidence worthy of study.

Of course, absence of evidence is not evidence of absence. Most scientists are open to the possibility that we might someday find evidence of alien visits, and many would welcome aliens with open arms. So far, however, we have no hard evidence to support the belief that aliens are already here.

Figure 18.20

In 1974, a short message was broadcast to the globular cluster M13 using the Arecibo radio telescope. The picture shown here was encoded by using two different radio frequencies, one for "on" and one for "off" (the colors shown here are arbitrary). To decode the message, the aliens would need to realize that the bits are meant to be arranged in a rectangular grid as shown, but that should not be difficult: The grid has 73 rows and 23 columns, and aliens would presumably know that these are both prime numbers. The picture represents the Arecibo radio dish, our solar system, a human stick figure, and a schematic of DNA and the eight simple molecules used in its construction.

made in 1974 with a radar transmitter on the Arecibo radio telescope, in which a simple pictorial message was beamed toward the globular cluster M13 (Figure 18.20). This target was chosen in part because it contains a few hundred thousand stars, seemingly offering a good chance that at least one has a civilization around it. However, M13 is about 25,000 light-years from Earth, so it will take some 25,000 years for our signal to get there and another 25,000 years for any response to make its way back to Earth.

Several SETI projects under way or in development would be capable of detecting signals like the one we broadcast from Arecibo if they came from civilizations within a few hundred light-years. These SETI efforts scan millions of radio frequency bands simultaneously. If anyone nearby is deliberately broadcasting on an ongoing basis, we have a good chance of detecting the signals.

think about it SETI efforts are often controversial because of their cost and uncertain chance of success, but supporters say the cost is justified because contact with an extraterrestrial intelligence would be such an important discovery. Do you agree? Defend your opinion.

18.5 Interstellar Travel and Its Implications to Civilization

So far, we have discussed ways of detecting distant civilizations without ever leaving the comfort of our own planet. Could we ever actually visit other worlds in other star systems? A careful analysis of this question turns out to have profound implications for the future of our civilization. To see why, we first need to consider the prospects for achieving interstellar travel.

• How difficult is interstellar travel?

In many science fiction movies, our descendants travel among the stars as routinely as we jet about the Earth in airplanes. They race around the galaxy in starships of all sizes and shapes, circumventing nature's prohibition on faster-than-light travel by entering hyperspace, wormholes, or warp drive. They witness firsthand incredible cosmic phenomena, such as stars and planets in all stages of development, accretion disks around white dwarfs and neutron stars, and the distortion of spacetime near black holes. Along the way they encounter numerous alien species, most of which happen to look and act a lot like us.

Unfortunately, Einstein's theory of relativity tells us that real interstellar travel must be at speeds slower than the speed of light, and even to approach that speed we will need to overcome huge technological hurdles. Nevertheless, we have already sent out our first emissaries to the stars, and there's no reason to believe that we won't develop better technologies in the future.

The Challenge of Interstellar Travel To date, we have launched five spacecraft that will leave our solar system and eventually travel among the stars: the planetary probes *Pioneer 10, Pioneer 11, Voyager 1,* and *Voyager 2* and the *New Horizons* spacecraft currently en route to

Pluto. These spacecraft are traveling about as fast as anything ever built by humans, but their speeds are still less than $\frac{1}{10{,}000}$ the speed of light. It would take each of them some 100,000 years just to reach the next nearest star system (Alpha Centauri), but their trajectories won't take them anywhere near it. Instead, they will simply continue their journey without passing close to any nearby stars, wandering the Milky Way for millions or even billions of years to come. The *Pioneer* and *Voyager* spacecraft carry greetings from Earth, just in case someone comes across one of them someday (Figure 18.21).

High-speed interstellar travel would require thousands of times as much energy as the entire world currently uses each year.

If we want to make interstellar journeys within human lifetimes, we will need starships that can travel at speeds close to the speed of light. We will need entirely new types of engines to reach such high speeds. The energy requirements of interstellar spacecraft may pose an even more daunting challenge. For example, the energy needed to accelerate a single ship the size of *Star Trek*'s *Enterprise* to just half the speed of light would be more than 2000 times the total annual energy use of the world today. Clearly, interstellar travel will require vast new sources of energy. In addition, fast-moving starships will require new types of shielding to protect crew members from instant death. As a starship travels through interstellar gas at near-light speed, ordinary atoms and ions will hit it like a deadly flood of high-energy cosmic rays.

If we succeed in building starships capable of traveling at speeds close to the speed of light, the crews will face significant social challenges. According to well-tested principles of Einstein's theory of relativity (see Special Topic: Relativity and the Cosmic Speed Limit, page 365), time will run much slower on a spaceship that travels at high speed to the stars than it does here on Earth. For example, in a ship traveling at an average speed of 99.9% of the speed of light, the 50-light-year round trip to the star Vega would take the travelers aboard only about 2 years—but more than 50 years would pass on Earth while they were gone. The crew would therefore need only 2 years' worth of provisions and would age only 2 years during the voyage, but they would return to a world quite different from the one they left. Family and friends would be older or deceased, new technologies might have made their knowledge and skills obsolete, and many political and social changes may have occurred in their absence. The crew would face a difficult adjustment when they came home to Earth.

Starship Design Despite all the difficulties, some scientists and engineers have already proposed designs that could in principle take us to nearby stars. In the 1960s, a group of scientists proposed *Project Orion,* which envisioned accelerating a spaceship with repeated detonations of relatively small hydrogen bombs. Each explosion would take place a few tens of meters behind the spaceship and would propel the ship forward as the vaporized debris impacted a "pusher plate" on the back of the spacecraft (Figure 18.22). Calculations showed that a spaceship accelerated by the rapid-fire detonation of a million H-bombs could reach Alpha Centauri in just over a century. In principle, we could build an *Orion* spacecraft with existing technology, though it would be very expensive and would require an exception to the international treaty banning nuclear detonations in space.

A century to the nearest star isn't bad, but it still wouldn't make interstellar travel easy. Unfortunately, no available technology could go

a The *Pioneer* plaque, about the size of an automobile license plate. The human figures are shown in front of a drawing of the spacecraft to give a sense of scale. The "prickly" graph to their left shows the Sun's position relative to nearby pulsars, and Earth's location around the Sun is shown below. Binary code indicates the pulsar periods; because pulsars slow with time, the periods allow someone reading the plaque to determine when the spacecraft was launched.

b *Voyagers 1* and *2* carry a phonograph record—a 12-inch gold-plated copper disk containing music, greetings, and images from Earth.

Figure 18.21

Messages aboard the *Pioneer* and *Voyager* spacecraft, which are bound for the stars.

Figure 18.22

Artist's conception of the *Project Orion* starship, showing one of the small hydrogen bomb detonations that would propel it. Debris from the detonation strikes the flat disk, called the pusher plate, at the back of the spaceship. The central sections (enclosed in a lattice) hold the bombs, and the front sections house the crew.

much faster. The problem is mass: Making a rocket faster requires more fuel, but adding fuel adds mass and makes it more difficult for the rocket to accelerate. Calculations show that even in the best case, rockets carrying nuclear fuel could achieve speeds no more than a few percent of the speed of light. Nevertheless, we can envision some possible future technologies that might get around this problem.

One idea suggests powering starships with engines that generate energy through matter–antimatter annihilation. Whereas nuclear fusion converts less than 1% of the mass of atomic nuclei into energy, matter–antimatter annihilation **[Section 17.1]** converts *all* the annihilated mass into energy. Starships with matter–antimatter engines could probably reach speeds of 90% or more of the speed of light. At these speeds, the slowing of time predicted by relativity becomes noticeable, putting many nearby stars within a few years' journey for the crew members. However, because no natural reservoirs of antimatter exist, we would have to be able to manufacture many tons of antimatter and then store it safely for the trip—capabilities that are far beyond our present means.

High-speed interstellar travel remains well beyond our current capabilities, but we can envision future technologies that could make it possible.

An even more speculative and futuristic design, known as an *interstellar ramjet,* would collect interstellar hydrogen with a gigantic scoop, using the collected gas as fuel for its nuclear engines (Figure 18.23). By collecting fuel along the way, the ship would not need to carry the weight of fuel on board. However, because the density of interstellar gas is so low, the scoop would need to be enormous. As astronomer Carl Sagan said, we are talking about "spaceships the size of worlds."

The bottom line is that while we face enormous obstacles to achieving interstellar travel, there's no reason to think it's impossible. If we can avoid self-destruction and if we continue to explore space, our descendants might well journey to the stars.

• Where are the aliens?

Imagine that we survive long enough to become interstellar travelers and that we begin to colonize habitable planets around nearby stars.

Figure 18.23

Artist's conception of a spaceship powered by an interstellar ramjet. The giant scoop in the front (left) collects interstellar hydrogen for use as fusion fuel.

As each colony grows, it may send out explorers to other star systems. Even if our starships traveled at relatively low speeds—say, a few percent of the speed of light—we could have dozens of outposts around nearby stars within a few centuries. In 10,000 years, our descendants would be spread among stars within a few hundred light-years of Earth. In a few million years, we could have outposts throughout the Milky Way Galaxy. We would have become a true galactic civilization.

Now, if we take the idea that *we* could develop a galactic civilization within a few million years and combine it with the reasonable (though unproved) idea that civilizations ought to be common, we are led to an astonishing conclusion: Someone else should already have created a galactic civilization.

To see why, let's take some sample numbers. Suppose the overall odds of a civilization arising around a star are about the same as your odds of winning the lottery, or 1 in a million. Taking a low estimate of 100 billion stars in the Milky Way Galaxy, this would mean there are some 100,000 civilizations in our galaxy alone. Moreover, current evidence suggests that stars and planetary systems like our own could have formed for at least 5 billion years before our solar system was even born, in which case the first of these 100,000 civilizations would have arisen at least 5 billion years ago. Others would have arisen, on average, about every 50,000 years. Under these assumptions, we would expect the youngest civilization besides ourselves to be some 50,000 years ahead of us technologically, and most would be millions or billions of years ahead of us.

If we can develop interstellar travel in the future, then it would seem that other civilizations should have developed the capability long ago.

We thereby encounter a strange paradox: Plausible arguments suggest that a galactic civilization should already exist, yet we have so far found no evidence of such a civilization. This paradox is often called *Fermi's paradox,* after the Nobel Prize–winning physicist Enrico Fermi. During a 1950 conversation with other scientists about the possibility of extraterrestrial intelligence, Fermi responded to speculations by asking, "So where is everybody?"

This paradox has many possible solutions, but broadly speaking we can group them into three categories:

1. *We are alone.* There is no galactic civilization because civilizations are extremely rare—so rare that we are the first to have arisen on the galactic scene, perhaps even the first in the universe.
2. *Civilizations are common, but no one has colonized the galaxy.* There are at least three possible reasons why this might be the case. Perhaps interstellar travel is much harder or more expensive than we have guessed, and civilizations are unable to venture far from their home worlds. Perhaps the desire to explore is unusual, and other societies either never leave their home star systems or stop exploring before they've colonized much of the galaxy. Most ominously, perhaps many civilizations have arisen, but they have all destroyed themselves before achieving the ability to colonize the stars.
3. *There IS a galactic civilization,* but it has not yet revealed its existence to us.

We do not know which, if any, of these explanations is the correct solution to the question "Where are the aliens?" However, each category of solution has astonishing implications for our own species.

Consider the first solution—that we are alone. If this is true, then our civilization is a remarkable achievement. It implies that through all of cosmic evolution, among countless star systems, we are the first piece of our galaxy or the universe ever to know that the rest of the universe exists. Through us, the universe has attained self-awareness. Some philosophers and many religions argue that the ultimate purpose of life is to become truly self-aware. If so, and if we are alone, then the destruction of our civilization and the loss of our scientific knowledge would represent an inglorious end to something that took the universe some 14 billion years to achieve. From this point of view, humanity becomes all the more precious, and the collapse of our civilization would be all the more tragic.

The second category of solutions has much more terrifying implications. If thousands of civilizations before us have all failed to achieve interstellar travel on a large scale, what hope do we have? Unless we somehow think differently than all other civilizations, this solution says that we will never go far in space. Because we have always explored when the opportunity arose, this solution almost inevitably leads to the conclusion that failure will come about because we destroy ourselves. We hope that this answer is wrong.

The third solution is perhaps the most intriguing. It says that we are newcomers on the scene of a galactic civilization that has existed for millions or billions of years before us. Perhaps this civilization is deliberately leaving us alone for the time being and will someday decide the time is right to invite us to join it.

No matter what the answer turns out to be, learning it will surely mark a turning point in the brief history of our species. Moreover, this turning point is likely to be reached within the next few decades or centuries. We already have the ability to destroy our civilization. If we do so, then our fate is sealed. But if we survive long enough to develop technology that can take us to the stars, the possibilities seem almost limitless.

the big picture

Putting Chapter 18 into Perspective

Throughout our study of astronomy, we have taken the "big picture" view of trying to understand how we fit into the universe. Here, at last, we have returned to Earth and examined the role of our own generation in the big picture of human history. Tens of thousands of past human generations have walked this Earth. Ours is the first generation with the technology to study the far reaches of our universe, to search for life elsewhere, and to travel beyond our home planet. It is up to us to decide whether we will use this technology to advance our species or to destroy it.

Imagine for a moment the grand view, a gaze across the centuries and millennia from this moment forward. Picture our descendants living among the stars, having created or joined a great galactic civilization. They will have the privilege of experiencing ideas, worlds, and discoveries far beyond our wildest imagination. Perhaps, in their history lessons, they will learn of our generation—the generation that history placed at the turning point and that managed to steer its way past the dangers of self-destruction and onto the path to the stars.

summary of key concepts

18.1 Life on Earth

• When did life arise on Earth?

Fossil evidence puts the origin of life at least 3.5 billion years ago, and carbon isotope evidence pushes this date to more than 3.85 billion years ago. Life therefore arose within a few hundred million years after Earth's birth, and possibly in a much shorter time.

• How did life arise on Earth?

Genetic evidence suggests that all life on Earth evolved from a common ancestor, which may have resembled microbes that live today in hot water near undersea volcanic vents or in hot springs. We do not know how this first organism arose, but laboratory experiments suggest that it may have been the result of natural chemical processes on the early Earth. Once life arose, it rapidly diversified and evolved through **natural selection**.

• What are the necessities of life?

Life on Earth thrives in a wide range of environments and in general seems to require only three things: a source of nutrients, a source of energy, and liquid water.

18.2 Life in the Solar System

• Could there be life on Mars?

Mars once had conditions that may have been conducive to an origin of life. If life arose, it might still survive in pockets of liquid water underground.

• Could there be life on Europa or other jovian moons?

Europa probably has a subsurface ocean of liquid water and may have undersea volcanoes on its ocean floor. If so, it has conditions much like those in which early life on Earth may have thrived, making it a good candidate for life. Ganymede and Callisto might have oceans as well. Titan has other liquids on its surface, though it is too cold for liquid water. Perhaps life can survive in these other liquids, or perhaps Titan has liquid water deep underground. Enceladus also shows evidence of subsurface liquids, offering yet another possibility for life.

18.3 Life Around Other Stars

• Are habitable planets likely?

Billions of stars have at least moderate-size **habitable zones** in which life-bearing planets might exist. We do not yet have the technology to search for habitable planets directly, but several planned missions should be able to begin the search soon.

• Are Earth-like planets rare or common?

We don't know. Arguments can be made on both sides of the question, and at present we lack the data to determine which answer is correct.

18.4 The Search for Extraterrestrial Intelligence

• How many civilizations are out there?

We don't know, but the **Drake equation** gives us a way to organize our thinking about the question. The equation (in a modified form) says that the number of civilizations in the Milky Way Galaxy with which we could potentially communicate is $N_{HP} \times f_{life} \times f_{civ} \times f_{now}$, where N_{HP} is the number of habitable planets in the galaxy, f_{life} is the fraction of habitable planets that actually have life on them, f_{civ} is the fraction of life-bearing planets upon which a civilization capable of interstellar communication has at some time arisen, and f_{now} is the fraction of all these civilizations that exist now.

• How does SETI work?

SETI, the search for extraterrestrial intelligence, generally refers to efforts to detect signals—such as radio or laser communications—coming from civilizations on other worlds.

18.5 Interstellar Travel and Its Implications to Civilization

• How difficult is interstellar travel?

Convenient interstellar travel remains well beyond our technological capabilities, because of the technological requirements for engines, the enormous energy needed to accelerate spacecraft to speeds near the speed of light, and the difficulties of shielding the crew from radiation. Nevertheless, people have proposed ways around all these difficulties, and it seems reasonable to think that we will someday achieve interstellar travel if we survive long enough.

• Where are the aliens?

A civilization capable of interstellar travel ought to be able to colonize the galaxy in a few million years or less, and the galaxy was around for billions of years before Earth was born. It therefore seems that someone should have colonized the galaxy long ago—yet we have no evidence of other civilizations. Every possible explanation for this surprising fact has astonishing implications for our species and our place in the universe.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 18 Visual Quiz at www.masteringastronomy.com.

The figure on page 530, which repeats Figure 18.3, shows the geological time scale. Use this figure to answer the following questions.

1. List the following events in the order in which they occurred, from first to last.
   a. earliest humans
   b. earliest animals
   c. impact causes extinction of dinosaurs
   d. earliest mammals
   e. earliest plants living on land
   f. first time there is significant oxygen in Earth's atmosphere
   g. first life on Earth
2. List the following time frames in order by how long they lasted, from the longest one to the shortest one.
   a. Hadean eon b. Proterozoic eon
   c. Paleozoic era d. Cretaceous period
3. Which of the following are time frames in which we are living today? More than one may apply.
   a. Quaternary period b. Tertiary period
   c. Cenozoic era d. Phanerozoic eon
   e. Paleozoic era
4. How long did the Cambrian explosion last?
   a. less than 1 year
   b. about a decade
   c. about 10,000 years
   d. about 40 million years
   e. about 500 million years
5. When did the heavy bombardment end?
   a. about 4.5 billion years ago
   b. between about 4.3 and 4.5 billion years ago
   c. between about 3.8 and 4.0 billion years ago
   d. exactly 3.85 billion years ago
6. How long have mammals been present on Earth?
   a. about 1 million years
   b. about 65 million years
   c. about 225 million years
   d. about 510 million years

exercises and problems

Mastering ASTRONOMY

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Describe three recent developments in the study of life on Earth that make life elsewhere seem more plausible.
2. How do we study the history of life on Earth? Describe the *geological time scale* and a few of the major events along it.
3. Summarize the evidence pointing to an early origin of life on Earth. How far back in Earth's history did life exist?
4. Why is the *theory of evolution* so critical to our understanding of the history of life on Earth? Explain how evolution proceeds by *natural selection,* and what happens to DNA that allows species to evolve.
5. Give a brief overview of the history of life on Earth. What evidence points to a common ancestor for all life? How and when did oxygen accumulate in Earth's atmosphere? When did larger animals diversify on Earth?
6. How are laboratory experiments helping us study the origin of life on Earth? Explain.
7. Is it possible that life migrated to Earth from elsewhere? Explain.
8. Describe the range of environments in which life thrives on Earth. What three basic requirements apply to life in all these environments?
9. What is a *habitable world?* Which worlds in our solar system seem potentially habitable, and why?
10. Briefly summarize the current status of the search for life on Mars.
11. What do we mean by a star's *habitable zone?* Do we expect many stars to be capable of having habitable planets? Explain.
12. What is the "rare Earth hypothesis"? Summarize the arguments on both sides regarding the validity of this hypothesis.
13. What is the *Drake equation?* Define each of its factors, and describe the current state of understanding about the potential values of each factor.
14. What is *SETI*? Describe the capabilities of current SETI efforts.
15. Why is interstellar travel so difficult? Describe a few technologies that might someday make it possible.
16. What is *Fermi's paradox*? Describe several potential solutions to the paradox, and the implications of each to our civilization.

Test Your Understanding

Fantasy or Science Fiction?

For each of the following futuristic scenarios, decide whether it is plausible or implausible according to our present understanding of science. Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

17. The first human explorers on Mars discover the ruins of an ancient civilization, including remnants of tall buildings and temples.
18. The first human explorers on Mars drill a hole into a Martian volcano to collect a sample of soil from deep underground. Upon analysis of the soil, they discover that it holds living microbes resembling terrestrial bacteria but with a different biochemistry.
19. In 2040, a spacecraft lands on Europa and melts its way through the ice into the Europan ocean. It finds numerous strange, living microbes, along with a few larger organisms that feed on the microbes.
20. It's the year 2075. A giant telescope on the Moon, consisting of hundreds of small telescopes linked together across a distance of 500 km, has just captured a series of images of a planet around a distant star that clearly show seasonal changes in vegetation.
21. A century from now, after completing a careful study of planets around stars within 100 light-years of Earth, astronomers discover that the most diverse life exists on a planet orbiting a young star that formed just 100 million years ago.

22. In 2030, a brilliant teenager working in her garage builds a coal-powered rocket that can travel at half the speed of light.
23. In the year 2750, we receive a signal from a civilization around a nearby star telling us that the *Voyager 2* spacecraft recently crash-landed on its planet.
24. Crew members of the matter–antimatter spacecraft *Star Apollo,* which left Earth in the year 2165, return to Earth in the year 2450, looking only a few years older than when they left.
25. Aliens from a distant star system invade Earth with the intent to destroy us and occupy our planet, but we successfully fight them off when their technology proves no match for ours.
26. A single great galactic civilization exists. It originated on a single planet long ago but is now made up of beings from many different planets, assimilated into the galactic culture.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Fossil evidence suggests that life on Earth arose (a) almost immediately after Earth formed. (b) within a few hundred million years after Earth formed. (c) about a billion years before the rise of the dinosaurs.
28. The theory of evolution is (a) a scientific theory, supported by extensive evidence. (b) one of several competing scientific models that all seem equally successful in explaining the nature of life on Earth. (c) essentially just a guess about how life changes through time.
29. Plants and animals are (a) the two major forms of life on Earth. (b) the only organisms that have DNA. (c) just two small branches of the diverse "tree of life" on Earth.
30. Which of the following is a reason why early living organisms on Earth probably could not have survived on the surface? (a) the lack of an ozone layer (b) the lack of oxygen for them to breathe (c) the fact that these organisms were single-celled
31. According to current understanding, a key requirement for life is (a) photosynthesis. (b) liquid water. (c) an ozone layer.
32. Which of the following worlds is *not* considered a candidate for harboring life? (a) Europa (b) Mars (c) the Moon
33. How does the habitable zone around a star of spectral type G compare to that around a star of spectral type M? (a) It is larger. (b) It is hotter. (c) It is closer to its star.
34. In the Drake equation, suppose that the term $f_{\text{life}} = \frac{1}{2}$. What would this mean? (a) Half the stars in the Milky Way Galaxy have a planet with life. (b) Half of all life forms in the universe are intelligent. (c) Half of the habitable worlds in the galaxy actually have life, while the other half don't.
35. The amount of energy that would be needed to accelerate a large spaceship to half the speed of light is (a) about 100 times as much energy as is needed to launch the Space Shuttle. (b) more than 2000 times the current annual global energy consumption. (c) more than the amount of energy released by a supernova.
36. According to current scientific understanding, the idea that the Milky Way Galaxy might be home to a civilization millions of years more advanced than ours is (a) a virtual certainty. (b) extremely unlikely. (c) one reasonable answer to Fermi's paradox.

Process of Science

37. *Extraordinary Claims.* As discussed in the chapter, both the *Viking* results and the study of a Martian meteorite led some scientists to think we had found evidence of life on Mars, even while most scientists disagreed. Those who disagree often point to Carl Sagan's dictum that "extraordinary claims require extraordinary evidence." Briefly discuss one of these cases, and decide whether you think it should require extraordinary evidence before being accepted. What follow-up evidence might lead scientists to re-evaluate their positions?
38. *Unanswered Questions.* In a sense, this entire chapter was about one big, unanswered question: Are we alone in the universe? But as we attempt to answer this "big" question, there are many smaller questions that we might wish to answer along the way. Describe one currently unanswered question about life in the universe that we might be able to answer with new missions or experiments over the next couple of decades. What kinds of evidence will we need to answer the question? How will we know when it is answered?

Group Work Exercise

39. *Habitable Planets?* In this exercise, you will rank several extrasolar planetary systems in order of the probability that they support life. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes). List the systems in order of most probable to least probable, and explain the reasons for your ranking in each case.
    a. a planet orbiting a star of spectral type B (approximately 10 solar masses) in a circular orbit with an average temperature expected to be 300 K
    b. a planet orbiting a Sun-like star in a circular orbit at a distance two times Earth's orbital distance from the Sun
    c. a planet orbiting a star with a luminosity one quarter the Sun's luminosity in a circular orbit at a distance one half Earth's orbital distance from the Sun
    d. a planet orbiting a Sun-like star in an elliptical orbit ranging from Earth's orbital distance to ten times Earth's orbital distance from the Sun

Investigate Further

Short-Answer/Essay Questions

40. *Most Likely to Have Life.* Suppose you were asked to vote in a contest to name the world in our solar system (besides Earth) "most likely to have life." Which world would you cast your vote for? Explain and defend your choice in a one-page essay.
41. *Likely Suns.* Study the stellar data for nearby stars given in Appendix F, Table F.1. Which star on the list would you expect to have the largest habitable zone? Which would have the second-largest habitable zone? If we rule out multiple-star systems, which star would you expect to have the highest probability of having a habitable planet? Explain your answers.
42. *Are Earth-like Planets Common?* Based on what you have learned in this book, do you think Earth-like planets will ultimately

prove to be rare, common, or something in between? Write a one- to two-page essay explaining and defending your opinion.

43. *Solution to the Fermi Paradox.* Among the various possible solutions to the question "Where are the aliens?," which do you think is most likely? Write a one- to two-page essay in which you explain why you favor this solution.
44. *What's Wrong with This Picture?* Many science fiction stories have imagined the galaxy divided into a series of empires, each having arisen from a different civilization on a different world, that hold each other at bay because they are all at about the same level of military technology. Is this a realistic scenario? Explain.
45. *Aliens in the Movies.* Choose a science fiction movie (or television show) that involves an alien species. Do you think aliens like this could really exist? Write a one- to two-page critical review of the movie, focusing primarily on the question of whether the movie portrays the aliens in a scientifically reasonable way.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

46. *SETI Search.* Suppose there are 10,000 civilizations broadcasting radio signals in the Milky Way Galaxy right now. On average, how many stars would we have to search before we would expect to hear a signal? Assume there are 500 billion stars in the galaxy. How does your answer change if there are only 100 civilizations instead of 10,000?
47. *SETI Signal.* Consider a civilization broadcasting a signal with a power of 10,000 watts. The Arecibo radio telescope, which is about 300 m in diameter, could detect this signal if it were coming from as far away as 100 light-years. Suppose instead that the signal is being broadcast from the other side of the Milky Way Galaxy, about 70,000 light-years away. How large a radio telescope would we need to detect this signal? (*Hint:* Use the inverse square law for light.)
48. *Cruise Ship Energy.* Suppose we have a spaceship about the size of a typical ocean cruise ship today, which means it has a mass of about 100 million kg, and we want to accelerate the ship to a speed of 10% of the speed of light.
    a. How much energy would be required? (*Hint:* You can find the answer simply by calculating the kinetic energy of the ship when it reaches its cruising speed; because 10% of the speed of light is still small compared to the speed of light, you can use the formula kinetic energy $= \frac{1}{2} \times m \times v^2$.)
    b. How does your answer compare to total worldwide energy use at present, which is about 5×10^{22} joules per year?
    c. The typical cost of energy today is roughly 5¢ per 1 million joules. Using this price, how much would it cost to generate the energy needed by this spaceship?
49. *Matter–Antimatter Engine.* Consider the spaceship from Problem 48. Suppose you want to generate the energy to get it to cruising speed using matter–antimatter annihilation. How much antimatter would you need to produce and take on the ship? (*Hint:* When matter and antimatter meet, they turn all their mass into energy equivalent to mc^2.)

Discussion Questions

50. *Funding the Search for Life.* Imagine that you are a member of Congress who decides how much government funding goes to research in different areas of science. How much would you allot to the search for life in the universe compared to the amount allotted to research in other areas of astronomy and planetary science? Why?
51. *Distant Dream or Near-Reality?* Considering all the issues surrounding interstellar flight, when (if ever) do you think we are likely to begin traveling among the stars? Why?
52. *The Turning Point.* Discuss the idea that our generation has acquired a greater responsibility for the future than any previous generation. Do you agree with this assessment? If so, how should we deal with this responsibility? Defend your opinion.

Web Projects

53. *Astrobiology News.* Go to NASA's astrobiology home page and read some of the articles about the search for life in the universe. Choose one recent article, and write a one- to two-page summary of the research and how it relates to the question of life in the universe.
54. *Martian Meteorites.* Research the latest discoveries concerning Martian meteorites. Choose one discovery and write a short summary of how you think it alters the debate about the habitability of Mars.
55. *The Search for Extraterrestrial Intelligence.* Go to the home page for the SETI Institute. Learn more about how SETI is funded and carried out, and summarize your findings in one page or less.
56. *Starship Design.* Read about a proposal for starship propulsion or design. How would the proposed starship work? What new technologies would be needed, and what existing technologies could be applied? Write a one- to two-page report on your research.
57. *Advanced Spacecraft Technologies.* NASA supports many efforts to incorporate new technologies into spaceships. Although few of them may be suitable for interstellar colonization, most are innovative and fascinating. Learn about one such NASA project, and write a short overview of your findings.

Part VI at a Glance. A Universe of Life?

Throughout this book, we have seen that the history of the universe has proceeded in a way that has made our existence on Earth possible. This figure summarizes some of the key ideas, and leads us to ask: If life arose here, shouldn't it also have arisen on many other worlds? We do not yet know the answer, but scientists are actively seeking to learn whether life is rare or common in the universe.

1 The protons, neutrons, and electrons in the atoms that make up Earth and life were created out of pure energy during the first few moments after the Big Bang, leaving the universe filled with hydrogen and helium gas [Section 17.1].

Matter can be created from energy: $E = mc^2$.

2 Ripples in the density of the early universe were necessary for life to form later on. Without those ripples, matter would never have collected into galaxies, stars, and planets [Section 17.3].

We observe the seeds of structure formation in the cosmic microwave background.

3 The attractive force of gravity pulls together the matter that makes galaxies, stars, and planets [Section 4.4].

Every piece of matter in the universe pulls on every other piece.

4 Our planet and all the life on it is made primarily of elements formed by nuclear fusion in high-mass stars and dispersed into space by supernovae [Section 12.3].

High-mass stars have cores hot enough to make elements heavier than carbon.

5 Our galaxy is large enough to retain the elements ejected by supernovae, and it recycles them into new stars and planetary systems [Section 14.2].

New elements mix with the interstellar medium, which then forms new stars and planets.

6 Planets can form in gaseous disks of material around newly formed stars. Earth was built from heavy elements that condensed from the gas as particles of metal and rock, which then gradually accreted to become our planet [Section 6.4].

Terrestrial planets formed in warm, inner regions of the solar nebula; jovian planets formed in cooler, outer regions.

7 Life as we know it requires liquid water, so we define the habitable zone around a star to be the zone in which a suitably large planet can have liquid water on its surface [Section 18.3].

The Sun's habitable zone (green) occupies a region from beyond the orbit of Venus to near the orbit of Mars.

8 Early life has had the time needed to evolve into complex forms—including us—because the solar thermostat has kept the Sun shining steadily for billions of years [Section 10.2].

The solar thermostat keeps the Sun's fusion rate stable.

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A Useful Numbers

Astronomical Distances

1 AU $\approx 1.496 \times 10^8$ km $= 1.496 \times 10^{11}$ m

1 light-year $\approx 9.46 \times 10^{12}$ km $= 9.46 \times 10^{15}$ m

1 parsec (pc) $\approx 3.09 \times 10^{13}$ km $\approx$ 3.26 light-years

1 kiloparsec (kpc) = 1000 pc $\approx 3.26 \times 10^3$ light-years

1 megaparsec (Mpc) $= 10^6$ pc $\approx 3.26 \times 10^6$ light-years

Universal Constants

Speed of light: $c = 3.00 \times 10^5$ km/s $= 3 \times 10^8$ m/s

Gravitational constant: $G = 6.67 \times 10^{-11} \dfrac{\text{m}^3}{\text{kg} \times \text{s}^2}$

Planck's constant: $h = 6.63 \times 10^{-34}$ joule $\times$ s

Stefan–Boltzmann constant: $\sigma = 5.67 \times 10^{-8} \dfrac{\text{watt}}{\text{m}^2 \times \text{K}^4}$

Mass of a proton: $m_\text{p} = 1.67 \times 10^{-27}$ kg

Mass of an electron: $m_\text{e} = 9.11 \times 10^{-31}$ kg

Useful Sun and Earth Reference Values

Mass of the Sun: $1M_\text{Sun} \approx 2 \times 10^{30}$ kg

Radius of the Sun: $1R_\text{Sun} \approx$ 696,000 km

Luminosity of the Sun: $1L_\text{Sun} \approx 3.8 \times 10^{26}$ watts

Mass of Earth: $1M_\text{Earth} \approx 5.97 \times 10^{24}$ kg

Radius (equatorial) of Earth: $1R_\text{Earth} \approx$ 6378 km

Acceleration of gravity on Earth: $g = 9.8$ m/s^2

Escape velocity from surface of Earth: $v_\text{escape} = 11$ km/s $= 11{,}000$ m/s

Astronomical Times

1 solar day (average) $= 24^\text{h}$

1 sidereal day $\approx 23^\text{h}56^\text{m}4.09^\text{s}$

1 synodic month (average) $\approx$ 29.53 solar days

1 sidereal month (average) $\approx$ 27.32 solar days

1 tropical year $\approx$ 365.242 solar days

1 sidereal year $\approx$ 365.256 solar days

Energy and Power Units

Basic unit of energy: 1 joule $= 1 \dfrac{\text{kg} \times \text{m}^2}{\text{s}^2}$

Basic unit of power: 1 watt = 1 joule/s

Electron-volt: 1 eV $= 1.60 \times 10^{-19}$ joule

B Useful Formulas

- Universal law of gravitation for the force between objects of mass M_1 and M_2, with distance d between their centers:

$$F = G\frac{M_1 M_2}{d^2}$$

- Newton's version of Kepler's third law, which applies to any pair of orbiting objects, such as a star and planet, a planet and moon, or two stars in a binary system; p is the orbital period, a is the distance between the centers of the orbiting objects, and M_1 and M_2 are the object masses:

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)}a^3$$

- Escape velocity at distance R from center of object of mass M:

$$v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

- Relationship between a photon's wavelength (λ), frequency (f), and the speed of light (c):

$$\lambda \times f = c$$

- Energy of a photon of wavelength λ or frequency f:

$$E = hf = \frac{hc}{\lambda}$$

- Stefan–Boltzmann law for thermal radiation at temperature T (in Kelvin):

$$\text{emitted power per unit area} = \sigma T^4$$

- Wien's law for the peak wavelength (λ_{max}) thermal radiation at temperature T (on the Kelvin scale):

$$\lambda_{\text{max}} = \frac{2{,}900{,}000}{T}\ \text{nm}$$

- Doppler shift (radial velocity is positive if the object is moving away from us and negative if it is moving toward us):

$$\frac{\text{radial velocity}}{\text{speed of light}} = \frac{\text{shifted wavelength} - \text{rest wavelength}}{\text{rest wavelength}}$$

- Angular separation (α) of two points with an actual separation s, viewed from a distance d (assuming d is much larger than s):

$$\alpha = \frac{s}{2\pi d} \times 360°$$

- Inverse square law for light (d is the distance to the object):

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi d^2}$$

- Parallax formula (distance d to a star with parallax angle p in arcseconds):

$$d\ (\text{in parsecs}) = \frac{1}{p\ (\text{in arcseconds})}$$

$$\text{or } d\ (\text{in light-years}) = 3.26 \times \frac{1}{p\ (\text{in arcseconds})}$$

- The orbital velocity law, to find the mass M_r contained within the circular orbit of radius r for an object moving at speed v:

$$M_r = \frac{r \times v^2}{G}$$

C A Few Mathematical Skills

THIS APPENDIX REVIEWS the following mathematical skills: powers of 10, scientific notation, working with units, the metric system, and finding a ratio. You should refer to this appendix as needed while studying the textbook.

C.1 Powers of 10

Powers of 10 indicate how many times to multiply 10 by itself. For example:

$$10^2 = 10 \times 10 = 100$$

$$10^6 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 1{,}000{,}000$$

Negative powers are the reciprocals of the corresponding positive powers. For example:

$$10^{-2} = \frac{1}{10^2} = \frac{1}{100} = 0.01$$

$$10^{-6} = \frac{1}{10^6} = \frac{1}{1{,}000{,}000} = 0.000001$$

Table C.1 lists powers of 10 from 10^{-12} to 10^{12}. Note that powers of 10 follow two basic rules:

1. A positive exponent tells how many zeros follow the 1. For example, 10^0 is a 1 followed by no zeros, and 10^8 is a 1 followed by eight zeros.
2. A negative exponent tells how many places are to the right of the decimal point, including the 1. For example, $10^{-1} = 0.1$ has one place to the right of the decimal point; $10^{-6} = 0.000001$ has six places to the right of the decimal point.

Multiplying and Dividing Powers of 10

Multiplying powers of 10 simply requires adding exponents, as the following examples show:

$$10^4 \times 10^7 = \underbrace{10{,}000}_{10^4} \times \underbrace{10{,}000{,}000}_{10^7} = \underbrace{100{,}000{,}000{,}000}_{10^{4+7} = 10^{11}} = 10^{11}$$

$$10^5 \times 10^{-3} = \underbrace{100{,}000}_{10^5} \times \underbrace{0.001}_{10^{-3}} = \underbrace{100}_{10^{5+(-3)} = 10^2} = 10^2$$

$$10^{-8} \times 10^{-5} = \underbrace{0.00000001}_{10^{-8}} \times \underbrace{0.00001}_{10^{-5}} = \underbrace{0.0000000000001}_{10^{-8+(-5)} = 10^{-13}} = 10^{-13}$$

Table C.1 *Powers of 10*

Zero and Positive Powers			Negative Powers		
Power	Value	Name	Power	Value	Name
10^0	1	One			
10^1	10	Ten	10^{-1}	0.1	Tenth
10^2	100	Hundred	10^{-2}	0.01	Hundredth
10^3	1000	Thousand	10^{-3}	0.001	Thousandth
10^4	10,000	Ten thousand	10^{-4}	0.0001	Ten-thousandth
10^5	100,000	Hundred thousand	10^{-5}	0.00001	Hundred-thousandth
10^6	1,000,000	Million	10^{-6}	0.000001	Millionth
10^7	10,000,000	Ten million	10^{-7}	0.0000001	Ten-millionth
10^8	100,000,000	Hundred million	10^{-8}	0.00000001	Hundred-millionth
10^9	1,000,000,000	Billion	10^{-9}	0.000000001	Billionth
10^{10}	10,000,000,000	Ten billion	10^{-10}	0.0000000001	Ten-billionth
10^{11}	100,000,000,000	Hundred billion	10^{-11}	0.00000000001	Hundred-billionth
10^{12}	1,000,000,000,000	Trillion	10^{-12}	0.000000000001	Trillionth

Dividing powers of 10 requires subtracting exponents, as in the following examples:

$$\frac{10^5}{10^3} = \underbrace{100{,}000}_{10^5} \div \underbrace{1000}_{10^3} = \underbrace{100}_{10^{5-3} = 10^2} = 10^2$$

$$\frac{10^3}{10^7} = \underbrace{1000}_{10^3} \div \underbrace{10{,}000{,}000}_{10^7} = \underbrace{0.0001}_{10^{3-7} = 10^{-4}} = 10^{-4}$$

$$\frac{10^{-4}}{10^{-6}} = \underbrace{0.0001}_{10^{-4}} \div \underbrace{0.000001}_{10^{-6}} = \underbrace{100}_{10^{-4-(-6)} = 10^2} = 10^2$$

Powers of Powers of 10

We can use the multiplication and division rules to raise powers of 10 to other powers or to take roots. For example:

$$(10^4)^3 = 10^4 \times 10^4 \times 10^4 = 10^{4+4+4} = 10^{12}$$

Note that we can get the same end result by simply multiplying the two powers:

$$(10^4)^3 = 10^{4\times 3} = 10^{12}$$

Because taking a root is the same as raising to a fractional power (e.g., the square root is the same as the $\frac{1}{2}$ power; the cube root is the same as the $\frac{1}{3}$ power, etc.), we can use the same procedure for roots, as in the following example:

$$\sqrt{10^4} = (10^4)^{1/2} = 10^{4\times(1/2)} = 10^2$$

Adding and Subtracting Powers of 10

Unlike multiplying and dividing powers of 10, there is no shortcut for adding or subtracting powers of 10. The values must be written in longhand notation. For example:

$$10^6 + 10^2 = 1{,}000{,}000 + 100 = 1{,}000{,}100$$
$$10^8 + 10^{-3} = 100{,}000{,}000 + 0.001 = 100{,}000{,}000.001$$
$$10^7 - 10^3 = 10{,}000{,}000 - 1000 = 9{,}999{,}000$$

Summary

We can summarize our findings using n and m to represent any numbers:

- To *multiply* powers of 10, *add* exponents: $10^n \times 10^m = 10^{n+m}$
- To *divide* powers of 10, *subtract* exponents: $\dfrac{10^n}{10^m} = 10^{n-m}$
- To *raise* powers of 10 to other powers, multiply exponents: $(10^n)^m = 10^{n\times m}$
- To add or subtract powers of 10, first write them out longhand.

C.2 Scientific Notation

When we are dealing with large or small numbers, it's generally easier to write them with powers of 10. For example, it's much easier to write the number 6,000,000,000,000 as 6×10^{12}. This format, in which a number *between* 1 and 10 is multiplied by a power of 10, is called **scientific notation.**

Converting a Number to Scientific Notation

We can convert numbers written in ordinary notation to scientific notation with a simple two-step process:

1. Move the decimal point to come after the *first* nonzero digit.
2. The number of places the decimal point moves tells you the power of 10; the power is *positive* if the decimal point moves to the left and *negative* if it moves to the right.

   Examples:

$$3042 \xrightarrow[\text{3 places to left}]{\text{decimal needs to move}} 3.042 \times 10^3$$

$$0.00012 \xrightarrow[\text{4 places to right}]{\text{decimal needs to move}} 1.2 \times 10^{-4}$$

$$226 \times 10^2 \xrightarrow[\text{2 places to left}]{\text{decimal needs to move}} (2.26 \times 10^2) \times 10^2 = 2.26 \times 10^4$$

Converting a Number from Scientific Notation

We can convert numbers written in scientific notation to ordinary notation by the reverse process:

1. The power of 10 indicates how many places to move the decimal point; move it to the *right* if the power of 10 is positive and to the *left* if it is negative.
2. If moving the decimal point creates any open places, fill them with zeros.

Examples:

$$4.01 \times 10^2 \xrightarrow[\text{2 places to right}]{\text{move decimal}} 401$$

$$3.6 \times 10^6 \xrightarrow[\text{6 places to right}]{\text{move decimal}} 3{,}600{,}000$$

$$5.7 \times 10^{-3} \xrightarrow[\text{3 places to left}]{\text{move decimal}} 0.0057$$

Multiplying or Dividing Numbers in Scientific Notation

Multiplying or dividing numbers in scientific notation simply requires operating on the powers of 10 and the other parts of the number separately.

Examples:

$$(6 \times 10^2) \times (4 \times 10^5) = (6 \times 4) \times (10^2 \times 10^5) = 24 \times 10^7 = (2.4 \times 10^1) \times 10^7 = 2.4 \times 10^8$$

$$\frac{4.2 \times 10^{-2}}{8.4 \times 10^{-5}} = \frac{4.2}{8.4} \times \frac{10^{-2}}{10^{-5}} = 0.5 \times 10^{-2-(-5)} = 0.5 \times 10^3 = (5 \times 10^{-1}) \times 10^3 = 5 \times 10^2$$

Note that, in both these examples, we first found an answer in which the number multiplied by a power of 10 was *not* between 1 and 10. We therefore followed the procedure for converting the final answer to scientific notation.

Addition and Subtraction with Scientific Notation

In general, we must write numbers in ordinary notation before adding or subtracting.

Examples:

$$(3 \times 10^6) + (5 \times 10^2) = 3{,}000{,}000 + 500 = 3{,}000{,}500 = 3.0005 \times 10^6$$

$$(4.6 \times 10^9) - (5 \times 10^8) = 4{,}600{,}000{,}000 - 500{,}000{,}000 = 4{,}100{,}000{,}000 = 4.1 \times 10^9$$

When both numbers have the *same* power of 10, we can factor out the power of 10 first.

Examples:

$$(7 \times 10^{10}) + (4 \times 10^{10}) = (7 + 4) \times 10^{10} = 11 \times 10^{10} = 1.1 \times 10^{11}$$

$$(2.3 \times 10^{-22}) - (1.6 \times 10^{-22}) = (2.3 - 1.6) \times 10^{-22} = 0.7 \times 10^{-22} = 7.0 \times 10^{-23}$$

C.3 Working with Units

Showing the units of a problem as you solve it usually makes the work much easier and also provides a useful way of checking your work. If an answer does not come out with the units you expect, you probably did something wrong. In general, working with units is very similar to working with numbers, as the following guidelines and examples show.

Five Guidelines for Working with Units

Before you begin any problem, think ahead and identify the units you expect for the final answer. Then operate on the units along with the numbers as you

solve the problem. The following five guidelines may be helpful when you are working with units:

1. Mathematically, it doesn't matter whether a unit is singular (e.g., meter) or plural (e.g., meters); we can use the same abbreviation (e.g., m) for both.
2. You cannot add or subtract numbers unless they have the *same* units. For example, 5 apples + 3 apples = 8 apples, but the expression 5 apples + 3 oranges cannot be simplified further.
3. You *can* multiply units, divide units, or raise units to powers. Look for key words that tell you what to do.
   - *Per* suggests division. For example, we write a speed of 100 kilometers per hour as

$$100\ \frac{\text{km}}{\text{hr}} \quad \text{or} \quad 100\ \frac{\text{km}}{1\ \text{hr}}$$

   - *Of* suggests multiplication. For example, if you launch a 50-kg space probe at a launch cost *of* \$10,000 per kilogram, the total cost is

$$50\ \cancel{\text{kg}} \times \frac{\$10{,}000}{\cancel{\text{kg}}} = \$500{,}000$$

   - *Square* suggests raising to the second power. For example, we write an area of 75 square meters as 75 m^2.
   - *Cube* suggests raising to the third power. For example, we write a volume of 12 cubic centimeters as 12 cm^3.
4. Often the number you are given is not in the units you wish to work with. For example, you may be given that the speed of light is 300,000 km/s but need it in units of m/s for a particular problem. To convert the units, simply multiply the given number by a *conversion factor:* a fraction in which the numerator (top of the fraction) and denominator (bottom of the fraction) are equal, so that the value of the fraction is 1; the number in the denominator must have the units that you wish to change. In the case of changing the speed of light from units of km/s to m/s, you need a conversion factor for kilometers to meters. Thus, the conversion factor is

$$\frac{1000\ \text{m}}{1\ \text{km}}$$

   Note that this conversion factor is equal to 1, since 1000 meters and 1 kilometer are equal, and that the units to be changed (km) appear in the denominator. We can now convert the speed of light from units of km/s to m/s simply by multiplying by this conversion factor:

$$\underbrace{300{,}000\ \frac{\cancel{\text{km}}}{\text{s}}}_{\substack{\text{speed of light}\\ \text{in km/s}}} \times \underbrace{\frac{1000\ \text{m}}{1\ \cancel{\text{km}}}}_{\substack{\text{conversion from}\\ \text{km to m}}} = \underbrace{3 \times 10^8\ \frac{\text{m}}{\text{s}}}_{\substack{\text{speed of light}\\ \text{in m/s}}}$$

   Note that the units of km cancel, leaving the answer in units of m/s.
5. It's easier to work with units if you replace division with multiplication by the reciprocal. For example, suppose you want to know how many minutes are represented by 300 seconds. We can find the answer by dividing 300 seconds by 60 seconds per minute:

$$300\ \text{s} \div 60\ \frac{\text{s}}{\text{min}}$$

However, it is easier to see the unit cancellations if we rewrite this expression by replacing the division with multiplication by the reciprocal (this process is easy to remember as "invert and multiply"):

$$300\text{ s} \div 60\frac{\text{s}}{\text{min}} = \underbrace{300\,\cancel{\text{s}} \times \underbrace{\frac{1\text{ min}}{60\,\cancel{\text{s}}}}_{\text{invert}}}_{\text{and multiply}} = 5\text{ min}$$

We now see that the units of seconds (s) cancel in the numerator of the first term and the denominator of the second term, leaving the answer in units of minutes.

More Examples of Working with Units

Example 1. How many seconds are there in 1 day?
Solution: We can answer the question by setting up a *chain* of unit conversions in which we start with 1 *day* and end up with *seconds*. We use the facts that there are 24 hours per day (24 hr/day), 60 minutes per hour (60 min/hr), and 60 seconds per minute (60 s/min):

$$\underbrace{1\,\cancel{\text{day}}}_{\substack{\text{starting}\\\text{value}}} \times \underbrace{\frac{24\,\cancel{\text{hr}}}{\cancel{\text{day}}}}_{\substack{\text{conversion}\\\text{from}\\\text{day to hr}}} \times \underbrace{\frac{60\,\cancel{\text{min}}}{\cancel{\text{hr}}}}_{\substack{\text{conversion}\\\text{from}\\\text{hr to min}}} \times \underbrace{\frac{60\text{ s}}{\cancel{\text{min}}}}_{\substack{\text{conversion}\\\text{from}\\\text{min to s}}} = 86{,}400\text{ s}$$

Note that all the units cancel except *seconds*, which is what we want for the answer. There are 86,400 seconds in 1 day.

Example 2. Convert a distance of 10^8 cm to km.
Solution: The easiest way to make this conversion is in two steps, since we know that there are 100 centimeters per meter (100 cm/m) and 1000 meters per kilometer (1000 m/km):

$$\underbrace{10^8\text{ cm}}_{\substack{\text{starting}\\\text{value}}} \times \underbrace{\frac{1\text{ m}}{100\text{ cm}}}_{\substack{\text{conversion}\\\text{from}\\\text{cm to m}}} \times \underbrace{\frac{1\text{ km}}{1000\text{ m}}}_{\substack{\text{conversion}\\\text{from}\\\text{m to km}}} = 10^8\,\cancel{\text{cm}} \times \frac{1\,\cancel{\text{m}}}{10^2\,\cancel{\text{cm}}} \times \frac{1\text{ km}}{10^3\,\cancel{\text{m}}} = 10^3\text{ km}$$

Alternatively, if we recognize that the number of kilometers should be smaller than the number of centimeters (because kilometers are larger), we might decide to do this conversion by dividing as follows:

$$10^8\text{ cm} \div \frac{100\text{ cm}}{\text{m}} \div \frac{1000\text{ m}}{\text{km}}$$

In this case, before carrying out the calculation, we replace each division with multiplication by the reciprocal:

$$\begin{aligned} 10^8\text{ cm} \div \frac{100\text{ cm}}{\text{m}} \div \frac{1000\text{ m}}{\text{km}} &= 10^8\text{ cm} \times \frac{1\text{ m}}{100\text{ cm}} \times \frac{1\text{ km}}{1000\text{ m}} \\ &= 10^8\,\cancel{\text{cm}} \times \frac{1\,\cancel{\text{m}}}{10^2\,\cancel{\text{cm}}} \times \frac{1\text{ km}}{10^3\,\cancel{\text{m}}} \\ &= 10^3\text{ km} \end{aligned}$$

Note that we again get the answer that 10^8 cm is the same as 10^3 km, or 1000 km.

Example 3. Suppose you accelerate at 9.8 m/s^2 for 4 seconds, starting from rest. How fast will you be going?
Solution: The question asked "how fast?" so we expect to end up with a speed. Therefore, we multiply the acceleration by the amount of time you accelerated:

$$9.8\,\frac{\text{m}}{\text{s}^2} \times 4\text{ s} = (9.8 \times 4)\,\frac{\text{m} \times \cancel{\text{s}}}{\text{s}^{\cancel{2}}} = 39.2\,\frac{\text{m}}{\text{s}}$$

Note that the units end up as a speed, showing that you will be traveling 39.2 m/s after 4 seconds of acceleration at 9.8 m/s^2.

Example 4. A reservoir is 2 km long and 3 km wide. Calculate its area, in both square kilometers and square meters.
Solution: We find its area by multiplying its length and width:

$$2\text{ km} \times 3\text{ km} = 6\text{ km}^2$$

Next we need to convert this area of 6 km^2 to square meters, using the fact that there are 1000 meters per kilometer (1000 m/km). Note that we must square the term 1000 m/km when converting from km^2 to m^2:

$$6\text{ km}^2 \times \left(1000\,\frac{\text{m}}{\text{km}}\right)^2 = 6\text{ km}^2 \times 1000^2\,\frac{\text{m}^2}{\text{km}^2} = 6\,\cancel{\text{km}^2} \times 1{,}000{,}000\,\frac{\text{m}^2}{\cancel{\text{km}^2}}$$

$$= 6{,}000{,}000\text{ m}^2$$

The reservoir area is 6 km^2, which is the same as 6 million m^2.

C.4 The Metric System (SI)

The modern version of the metric system, known as *Système Internationale d'Unites* (French for "International System of Units") or **SI,** was formally established in 1960. Today, it is the primary measurement system in nearly every country in the world with the exception of the United States. Even in the United States, it is the system of choice for science and international commerce. The basic units of length, mass, and time in the SI are

- The **meter** for length, abbreviated m
- The **kilogram** for mass, abbreviated kg
- The **second** for time, abbreviated s

Multiples of metric units are formed by powers of 10, using a prefix to indicate the power. For example, *kilo* means 10^3 (1000), so a kilometer is 1000 meters; a microgram is 0.000001 gram, because *micro* means 10^{-6}, or one millionth. Some of the more common prefixes are listed in Table C.2.

Table C.2 *SI (Metric) Prefixes*

Small Values			Large Values		
Prefix	Abbreviation	Value	Prefix	Abbreviation	Value
Deci	d	10^{-1}	Deca	da	10^{1}
Centi	c	10^{-2}	Hecto	h	10^{2}
Milli	m	10^{-3}	Kilo	k	10^{3}
Micro	μ	10^{-6}	Mega	M	10^{6}
Nano	n	10^{-9}	Giga	G	10^{9}
Pico	p	10^{-12}	Tera	T	10^{12}

Table C.3 *Metric Conversions*

To Metric	From Metric
1 inch = 2.540 cm	1 cm = 0.3937 inch
1 foot = 0.3048 m	1 m = 3.28 feet
1 yard = 0.9144 m	1 m = 1.094 yards
1 mile = 1.6093 km	1 km = 0.6214 mile
1 pound = 0.4536 kg	1 kg = 2.205 pounds

Metric Conversions

Table C.3 lists conversions between metric units and units used commonly in the United States. Note that the conversions between kilograms and pounds are valid only on Earth, because they depend on the strength of gravity.

Example 1. International athletic competitions generally use metric distances. Compare the length of a 100-meter race to that of a 100-yard race.
Solution: Table C.3 shows that 1 m = 1.094 yd, so 100 m is 109.4 yd. Note that 100 meters is almost 110 yards; a good "rule of thumb" to remember is that distances in meters are about 10% longer than the corresponding number of yards.

Example 2. How many square kilometers are in 1 square mile?
Solution: We use the square of the miles-to-kilometers conversion factor:

$$(1\ \text{mi}^2) \times \left(\frac{1.6093\ \text{km}}{1\ \text{mi}}\right)^2 = (1\ \cancel{\text{mi}^2}) \times \left(1.6093^2\ \frac{\text{km}^2}{\cancel{\text{mi}^2}}\right) = 2.5898\ \text{km}^2$$

Therefore, 1 square mile is 2.5898 square kilometers.

C.5 Finding a Ratio

Suppose you want to compare two quantities, such as the average density of Earth and the average density of Jupiter. The way we do such a comparison is by dividing, which tells us the *ratio* of the two quantities. In this case, Earth's average density is 5.52 g/cm^3 and Jupiter's average density is 1.33 g/cm^3 (see Figure 8.1), so the ratio is

$$\frac{\text{average density of Earth}}{\text{average density of Jupiter}} = \frac{5.52\ \cancel{\text{g/cm}^3}}{1.33\ \cancel{\text{g/cm}^3}} = 4.15$$

Notice how the units cancel on both the top and bottom of the fraction. We can state our result in two equivalent ways:

- The ratio of Earth's average density to Jupiter's average density is 4.15.
- Earth's average density is 4.15 times Jupiter's average density.

Sometimes, the quantities that you want to compare may each involve an equation. In such cases, you could, of course, find the ratio by first calculating each of the two quantities individually and then dividing. However, it is much easier if you first express the ratio as a fraction, putting the equation for one quantity on top and the other on the bottom. Some of the terms in the equation may then cancel out, making any calculations much easier.

Example 1. Compare the kinetic energy of a car traveling at 100 km/hr to that of a car traveling at 50 km/hr.

Solution: We do the comparison by finding the ratio of the two kinetic energies, recalling that the formula for kinetic energy is $\frac{1}{2}mv^2$. Since we are not told the mass of the car, you might at first think that we don't have enough information to find the ratio. However, notice what happens when we put the equations for each kinetic energy into the ratio, calling the two speeds v_1 and v_2:

$$\frac{\text{K.E. car at } v_1}{\text{K.E. car at } v_2} = \frac{\frac{1}{2}\cancel{m}_{\text{car}}v_1^2}{\frac{1}{2}\cancel{m}_{\text{car}}v_2^2} = \frac{v_1^2}{v_2^2} = \left(\frac{v_1}{v_2}\right)^2$$

All the terms cancel except those with the two speeds, leaving us with a very simple formula for the ratio. Now we put in 100 km/hr for v_1 and 50 km/hr for v_2:

$$\frac{\text{K.E. car at 100 km/hr}}{\text{K.E. car at 50 km/hr}} = \left(\frac{100\ \cancel{\text{km/hr}}}{50\ \cancel{\text{km/hr}}}\right)^2 = 2^2 = 4$$

The ratio of the car's kinetic energies at 100 km/hr and 50 km/hr is 4. That is, the car has four times as much kinetic energy at 100 km/hr as it has at 50 km/hr.

Example 2. Compare the strength of gravity between Earth and the Sun to the strength of gravity between Earth and the Moon.
Solution: We do the comparison by taking the ratio of the Earth–Sun gravity to the Earth–Moon gravity. In this case, each quantity is found from the equation of Newton's law of gravity. (See Section 4.4.) Thus, the ratio is

$$\frac{\text{Earth–Sun gravity}}{\text{Earth–Moon gravity}} = \frac{\cancel{G}\dfrac{\cancel{M_{\text{Earth}}}M_{\text{Sun}}}{(d_{\text{Earth–Sun}})^2}}{\cancel{G}\dfrac{\cancel{M_{\text{Earth}}}M_{\text{Moon}}}{(d_{\text{Earth–Moon}})^2}} = \frac{M_{\text{Sun}}}{(d_{\text{Earth–Sun}})^2} \times \frac{(d_{\text{Earth–Moon}})^2}{M_{\text{Moon}}}$$

Note how all but four of the terms cancel; the last step comes from replacing the division with multiplication by the reciprocal (the "invert and multiply" rule for division). We can simplify the work further by rearranging the terms so that we have the masses and distances together:

$$\frac{\text{Earth}-\text{Sun gravity}}{\text{Earth}-\text{Moon gravity}} = \frac{M_{\text{Sun}}}{M_{\text{Moon}}} \times \frac{(d_{\text{Earth}-\text{Moon}})^2}{(d_{\text{Earth}-\text{Sun}})^2}$$

Now it is just a matter of looking up the numbers (see Appendix E) and calculating:

$$\frac{\text{Earth}-\text{Sun gravity}}{\text{Earth}-\text{Moon gravity}} = \frac{1.99 \times 10^{30}\ \cancel{\text{kg}}}{7.35 \times 10^{22}\ \cancel{\text{kg}}} \times \frac{(384.4 \times 10^3\ \cancel{\text{km}})^2}{(149.6 \times 10^6\ \cancel{\text{km}})^2} = 179$$

In other words, the Earth–Sun gravity is 179 times stronger than the Earth–Moon gravity.

D The Periodic Table of the Elements

Key

12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1 **H** Hydrogen 1.00794																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.01218											5 **B** Boron 10.81	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007	8 **O** Oxygen 15.999	9 **F** Fluorine 18.988	10 **Ne** Neon 20.179
11 **Na** Sodium 22.990	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.974	16 **S** Sulfur 32.06	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
19 **K** Potassium 39.098	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.956	22 **Ti** Titanium 47.88	23 **V** Vanadium 50.94	24 **Cr** Chromium 51.996	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.847	27 **Co** Cobalt 58.9332	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.59	33 **As** Arsenic 74.922	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.468	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.9059	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.906	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.868	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.75	52 **Te** Tellurium 127.60	53 **I** Iodine 126.905	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.91	56 **Ba** Barium 137.34		72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.85	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.2	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.967	80 **Hg** Mercury 200.59	81 **Ti** Thallium 204.383	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium 226.0254		104 **Rf** Rutherfordium (263)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (267)	108 **Hs** Hassium (277)	109 **Mt** Meitnerium (268)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (272)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Uuq** Ununquadium (289)	115 **Uup** Ununpentium (288)	116 **Uuh** Ununhexium (292)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanide Series

57 **La** Lanthanum 138.906	58 **Ce** Cerium 140.12	59 **Pr** Praseodymium 140.908	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.96	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.934	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967

Actinide Series

89 **Ac** Actinium 227.028	90 **Th** Thorium 232.038	91 **Pa** Protactinium 231.036	92 **U** Uranium 238.029	93 **Np** Neptunium 237.048	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (260)

E Planetary Data

Table E.1 *Physical Properties of the Sun and Planets*

Name	Radius (Eq[a]) (km)	Radius (Eq) (Earth units)	Mass (kg)	Mass (Earth units)	Average Density (g/cm^3)	Surface Gravity (Earth = 1)	Escape Velocity (km/s)
Sun	695,000	109	1.99×10^{30}	333,000	1.41	27.5	—
Mercury	2440	0.382	3.30×10^{23}	0.055	5.43	0.38	4.43
Venus	6051	0.949	4.87×10^{24}	0.815	5.25	0.91	10.4
Earth	6378	1.00	5.97×10^{24}	1.00	5.52	1.00	11.2
Mars	3397	0.533	6.42×10^{23}	0.107	3.93	0.38	5.03
Jupiter	71,492	11.19	1.90×10^{27}	317.9	1.33	2.36	59.5
Saturn	60,268	9.46	5.69×10^{26}	95.18	0.70	0.92	35.5
Uranus	25,559	3.98	8.66×10^{25}	14.54	1.32	0.91	21.3
Neptune	24,764	3.81	1.03×10^{26}	17.13	1.64	1.14	23.6
Pluto[b]	1160	0.181	1.31×10^{22}	0.0022	2.05	0.07	1.25
Eris[b]	1430	0.22	1.66×10^{22}	0.0028	2.30	0.08	1.4

[a]Eq = equatorial.

[b]Under the IAU definitions of August 2006, Pluto and Eris are officially designated "dwarf planets."

Table E.2 *Orbital Properties of the Sun and Planets*

Name	Distance from Sun[a] (AU)	Distance from Sun[a] (10^6 km)	Orbital Period (years)	Orbital Inclination[b] (degrees)	Orbital Eccentricity	Sidereal Rotation Period (Earth days)[c]	Axis Tilt (degrees)
Sun	—	—	—	—	—	25.4	7.25
Mercury	0.387	57.9	0.2409	7.00	0.206	58.6	0.0
Venus	0.723	108.2	0.6152	3.39	0.007	−243.0	177.3
Earth	1.00	149.6	1.0	0.00	0.017	0.9973	23.45
Mars	1.524	227.9	1.881	1.85	0.093	1.026	25.2
Jupiter	5.203	778.3	11.86	1.31	0.048	0.41	3.08
Saturn	9.539	1427	29.42	2.48	0.056	0.44	26.73
Uranus	19.19	2870	84.01	0.77	0.046	−0.72	97.92
Neptune	30.06	4497	164.8	1.77	0.010	0.67	29.6
Pluto	39.48	5906	248.0	17.14	0.248	−6.39	112.5
Eris	67.67	10,120	557	44.19	0.442	15.8	78

[a]Semimajor axis of the orbit.
[b]With respect to the ecliptic.
[c]A negative sign indicates rotation is backward relative to other planets.

Table E.3 *Satellites of the Solar System (as of 2009)*[a]

Planet Satellite	Radius or Dimensions[b] (km)	Distance from Planet (10^3 km)	Orbital Period[c] (Earth days)	Mass[d] (kg)	Density[d] (g/cm^3)	Notes About the Satellite
Earth						**Earth**
Moon	1738	384.4	27.322	7.349×10^{22}	3.34	*Moon:* Probably formed in giant impact.
Mars						**Mars**
Phobos	$13 \times 11 \times 9$	9.38	0.319	1.3×10^{16}	1.9	*Phobos, Deimos:* Probable captured asteroids.
Deimos	$8 \times 6 \times 5$	23.5	1.263	1.8×10^{15}	2.2	
Jupiter						**Jupiter**
Small inner moons (4 moons)	8 to 83	128–222	0.295–0.674	—	—	*Metis, Adrastea, Amalthea, Thebe:* Small moonlets within and near Jupiter's ring system.
Io	1821	421.6	1.769	8.933×10^{22}	3.57	*Io:* Most volcanically active object in the solar system.
Europa	1565	670.9	3.551	4.797×10^{22}	2.97	*Europa*: Possible oceans under icy crust.
Ganymede	2634	1070.0	7.155	1.482×10^{23}	1.94	*Ganymede:* Largest satellite in solar system; unusual ice geology.
Callisto	2403	1883.0	16.689	1.076×10^{23}	1.86	*Callisto:* Cratered iceball.
Irregular group 1 (7 moons)	4–85	7200–17,000	130–457	—	—	*Themisto, Leda, Himalia, Lysithea, Elara, and others:* Probable captured moons with inclined orbits.
Irregular group 2 (48 moons)	1–30	15,900–29,500	2490 to 2983	—	—	*Ananke, Carme, Pasiphae, Sinope, and others:* Probable captured moons in inclined backward orbits.
Saturn						**Saturn**
Small inner moons (11)	3–89	134–212	0.574–1.1	—	—	*Pan, Atlas, Prometheus, Pandora, Epimetheus, Janus, and others:* Small moonlets within and near Saturn's ring system.
Mimas	199	185.52	0.942	3.70×10^{19}	1.17	*Mimas, Enceladus, Tethys:* Small and medium-size iceballs, many with interesting geology.
Enceladus	249	238.02	1.370	1.2×10^{20}	1.24	
Tethys	530	294.66	1.888	6.17×10^{20}	1.26	
Calypso and Telesto	8–12	294.66	1.888	—	—	*Calypso and Telesto:* Small moonlets sharing Tethys's orbit.
Dione	559	377.4	2.737	1.08×10^{21}	1.44	*Dione:* Medium-size iceball, with interesting geology.
Helene and Polydeuces	2–16	377.4	2.737	1.6×10^{16}	—	*Helene and Polydeuces:* Small moonlets sharing Dione's orbit.
Rhea	764	527.04	4.518	2.31×10^{21}	1.33	*Rhea:* Medium-size iceball, with interesting geology.
Titan	2575	1221.85	15.945	1.35×10^{23}	1.88	*Titan:* Dense atmosphere shrouds surface; ongoing geological activity.
Hyperion	$180 \times 140 \times 112$	1481.1	21.277	2.8×10^{19}	—	*Hyperion:* Only satellite known not to rotate synchronously.
Iapetus	718	3561.3	79.331	1.59×10^{21}	1.21	*Iapetus:* Bright and dark hemispheres show greatest contrast in the solar system.

Phoebe	110	12,952	−550.4	1×10^{19}	—	*Phoebe:* Very dark; material ejected from Phoebe may coat one side of Iapetus.
Irregular groups (25 moons)	2–16	11,400–23,400	450–930 −550 to −1320	—	—	Probable captured moons with highly inclined and/or backward orbits.
Uranus						**Uranus**
Small inner moons (13 moons)	5–81	49–98	0.4–0.9	—	—	*Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, Cupid, Belinda, Perdita, Puck, Mab, 1986 U10, 2003 U1, 2003 U3:* Small moonlets within and near Uranus's ring system.
Miranda	236	129.8	1.413	6.6×10^{19}	1.26	*Miranda, Ariel, Umbriel, Titania, Oberon:* Small and medium-size iceballs, with some interesting geology.
Ariel	579	191.2	2.520	1.35×10^{21}	1.65	
Umbriel	584.7	266.0	4.144	1.17×10^{21}	1.44	
Titania	788.9	435.8	8.706	3.52×10^{21}	1.59	
Oberon	761.4	582.6	13.463	3.01×10^{21}	1.50	
Irregular group (9 moons)	5–95	4280–21,000	580–2820	—	—	*Francisco, Caliban, Stephano, Trinculo, Sycorax, Margaret, Prospero, Setebos, Ferdinand, 2001 U2, 2001 U3, 2003 U3:* Probable captured moons; several in backward orbits.
Neptune						**Neptune**
Small inner moons (5 moons)	29–86	48–74	0.30–0.55	—	—	*Naiad, Thalassa, Despina, Galatea, Larissa:* Small moonlets within and near Neptune's ring system.
Proteus	218 × 208 × 201	117.6	1.121	6×10^{19}	—	
Triton	1352.6	354.59	−5.875	2.14×10^{22}	2.0	*Triton:* Probable captured Kuiper belt object—largest captured object in solar system.
Nereid	170	5588.6	360.125	3.1×10^{19}	—	*Nereid:* Small, icy moon; very little known.
Irregulars (5 moons)	15–27	16,600–48,600	1870–9412	—	—	*2002 N1, N2, N3, N4, 2003 N1:* Possible captured moons in inclined or backward orbit.
Pluto						**Pluto**
Charon	593	19.6	6.38718	1.56×10^{21}	1.6	*Charon:* Unusually large compared to Pluto; may have formed in giant impact.
Nix	50	48,680	24.9	—	—	*Nix and Hydra:* Newly discovered moons outside Charon's orbit.
Hydra	75	64,780	38.2	—	—	
Eris						**Eris**
Dysnomia	50	37,000	15.8	—	—	*Dysnomia:* Approximate properties determined in June 2007.

[a]*Note:* Authorities differ substantially on many of the values in this table.

[b] $a \times b \times c$ values for the dimensions are the approximate lengths of the axes (center to edge) for irregular moons.

[c]Negative sign indicates backward orbit.

[d]Masses and densities are most accurate for those satellites visited by a spacecraft on a flyby. Masses for the smallest moons have not been measured but can be estimated from the radius and an assumed density.

Table E.4 *Fifty Extrasolar Planets of Note (listed in order of distance from their star)*

Name	Detection Methods	Minimum Mass (Jupiter masses)	Semimajor Axis (AU)	Period (days)	Radius (Jupiter radii)	Stellar Mass (Solar masses)	Notes
Gliese 876 d	radial velocity	0.018	0.02081	1.93776	—	0.32	hot Jupiter; sub-Uranus mass; least massive planet confirmed as of 2007
OGLE-TR-56 b	transit, radial velocity	1.29	0.0225	1.21191	1.30	1.17	hot Jupiter; first planet discovered by transit; planet with the shortest confirmed period as of 2007
GJ 436 b	radial velocity	0.0713	0.0285	2.64385	—	0.44	hot Jupiter; sub-Saturn mass
SWEEPS-11	transit, radial velocity	9.7	0.03	1.796	1.13	1.10	hot Jupiter
OGLE-TR-132 b	transit, radial velocity	1.14	0.0306	1.68986	1.18	1.26	hot Jupiter
WASP-2 b	transit, radial velocity	0.88	0.0307	2.15223	1.04	0.79	hot Jupiter
TrES-2	transit, radial velocity	1.98	0.0367	2.47063	1.22	0.98	hot Jupiter
55 Cnc e	radial velocity	0.045	0.038	2.81	—	1.03	hot Jupiter; sub-Neptune mass
WASP-1 b	transit, radial velocity	0.89	0.0382	2.51997	1.44	1.15	hot Jupiter; "puffed-up planet"
TrES-1	transit, radial velocity, eclipse	0.61	0.0393	3.03007	1.081	0.87	hot Jupiter
HD 46375 b	radial velocity	0.249	0.041	3.024	—	0.91	hot Jupiter; sub-Saturn mass
Gliese 581 b	radial velocity	0.0492	0.041	5.3683	—	0.31	—
OGLE-TR-10 b	transit, radial velocity	0.63	0.04162	3.10129	1.26	1.18	hot Jupiter
HD 149026 b	radial velocity, transit	0.36	0.042	2.8766	0.725	1.3	hot Jupiter
HD 209458 b	radial velocity, transit, eclipse	0.69	0.045	3.52475	1.32	1.01	hot Jupiter; "puffed-up planet"; first planet and first atmosphere successfully detected by transit
HD 88133 b	radial velocity	0.22	0.047	3.41	—	1.20	hot Jupiter; sub-Saturn mass
OGLE-TR-111 b	transit, radial velocity	0.53	0.047	4.01445	1.067	0.82	hot Jupiter
XO-1 b	transit, radial velocity	0.9	0.0488	3.94153	1.184	1.00	hot Jupiter
51 Peg b	radial velocity	0.468	0.052	4.23077	—	1.06	hot Jupiter; first exoplanet discovered around Sun-like star
SWEEPS-04	transit, radial velocity	3.8	0.055	4.2	0.81	1.24	hot Jupiter
HAT—P-1 b	transit, radial velocity	0.53	0.0551	4.46529	1.36	1.12	hot Jupiter; "puffed-up planet"
Ups And b	radial velocity	0.69	0.059	4.61708	—	1.27	hot Jupiter; in first multiplanet system discovered around Sun-like star
Gliese 581 c	radial velocity	0.0158	0.073	12.932	—	0.31	—
HD 160691 d	radial velocity	0.044	0.09	9.55	—	1.08	hot Jupiter; sub-Uranus mass
55 Cnc b	radial velocity	0.784	0.115	14.67	—	1.03	—
Gliese 876 c	radial velocity	0.56	0.13	30.1	—	0.32	eccentric

HD 102117 b	radial velocity	0.172	0.1532	20.67	—	0.95	sub-Saturn mass
Gliese 876 b	radial velocity	1.935	0.20783	60.94	—	0.32	first exoplanet discovered orbiting a red dwarf
55 Cnc c	radial velocity	0.217	0.24	43.93	—	1.03	eccentric; sub-Saturn mass
Gliese 581 d	radial velocity	0.0243	0.25	83.60	—	0.31	—
HD 16141 b	radial velocity	0.23	0.35	75.56	—	1.00	sub-Saturn mass
HD 80606 b	radial velocity	3.41	0.439	111.78	—	0.9	eccentric; highest known planetary eccentricity (0.927)
HD 82943 c	radial velocity	2.01	0.746	219.0	—	1.18	eccentric
Ups And c	radial velocity	1.98	0.83	241.52	—	1.27	eccentric; in first multiplanet system discovered around Sun-like star
HR 810 b	radial velocity	1.94	0.91	311.288	—	1.11	—
HD 210277 b	radial velocity	1.23	1.10	442.1	—	0.92	eccentric; planet mass partially inferred from surrounding disk
HD 27442 b	radial velocity	1.28	1.18	423.841	—	1.2	—
HD 41004 A b	radial velocity	2.3	1.31	655.0	—	0.7	eccentric; planet in a system with two stars and a brown dwarf
HD 4208 b	radial velocity	0.80	1.67	812.197	—	0.93	—
HD 45350 b	radial velocity	1.79	1.92	890.76	—	1.02	—
Gamma Cephei b	radial velocity	1.60	2.044	902.9	—	1.4	first extrasolar planet discovered in close stellar binary system
HD 187085 b	radial velocity	0.75	2.05	986.0	—	1.22	eccentric
47 Uma b	radial velocity	2.60	2.11	1083.2	—	1.03	—
HD 10697 b	radial velocity	6.12	2.13	1077.906	—	1.15	—
Ups And d	radial velocity	3.95	2.51	1274.6	—	1.27	in first multiplanet system discovered around Sun-like star
HD 202206 c	radial velocity	2.44	2.55	1383.4	—	1.13	eccentric
HD 37124 c	radial velocity	0.683	3.19	2295.0	—	0.91	—
Epsilon Eridani b	radial velocity, astrometry	1.55	3.39	2502.0	—	0.83	eccentric; star surrounded by dust disk; closest in distance exoplanet to Earth
HD 38529 c	radial velocity	12.7	3.68	2174.3	—	1.39	eccentric
HD 72659 b	radial velocity	2.96	4.16	3177.4	—	0.95	—
55 Cnc d	radial velocity	3.92	5.257	4517.4	—	1.03	eccentric; largest confirmed semimajor axis as of 2007
2M1207 b	direct imaging	~5	~41 −51	—	1.50	0.025	only confirmed image detection of exoplanet; orbit very uncertain but mass well-constrained

Notes: 1. The list includes all planets detected by two methods, most planets in multiple systems, most hot Jupiters, and a representative sample of other extrasolar planets. More than 200 known extrasolar planets are not listed.

2. Where two detection methods are listed, the discovery method is given first.

3. *Eccentric* means eccentricity > 0.25.

F Stellar Data

Table F.1 *Stars Within 12 Light-Years*

Star	Distance (ly)	Spectral Type		RA h	RA m	Dec °	Dec ′	Luminosity (L/L_{Sun})
Sun	0.000016	G2	V	—	—	—	—	1.0
Proxima Centauri	4.2	M5.0	V	14	30	−62	41	0.0006
α Centauri A	4.4	G2	V	14	40	−60	50	1.6
α Centauri B	4.4	K0	V	14	40	−60	50	0.53
Barnard's Star	6.0	M4	V	17	58	+04	42	0.005
Wolf 359	7.8	M5.5	V	10	56	+07	01	0.0008
Lalande 21185	8.3	M2	V	11	03	+35	58	0.03
Sirius A	8.6	A1	V	06	45	−16	42	26.0
Sirius B	8.6	DA2	White dwarf	06	45	−16	42	0.002
BL Ceti	8.7	M5.5	V	01	39	−17	57	0.0009
UV Ceti	8.7	M6	V	01	39	−17	57	0.0006
Ross 154	9.7	M3.5	V	18	50	−23	50	0.004
Ross 248	10.3	M5.5	V	23	42	+44	11	0.001
ε Eridani	10.5	K2	V	03	33	−09	28	0.37
Lacaille 9352	10.7	M1.0	V	23	06	−35	51	0.05
Ross 128	10.9	M4	V	11	48	+00	49	0.003
EZ Aquarii A	11.3	M5	V	22	39	−15	18	0.0006
EZ Aquarii B	11.3	—	—	22	39	−15	18	0.0004
EZ Aquarii C	11.3	—	—	22	39	−15	18	0.0003
61 Cygni A	11.4	K5	V	21	07	+38	42	0.17
61 Cygni B	11.4	K7	V	21	07	+38	42	0.10
Procyon A	11.4	F5	IV–V	07	39	+05	14	8.6
Procyon B	11.4	DA	White dwarf	07	39	+05	14	0.0005
Gliese 725 A	11.5	M3	V	18	43	+59	38	0.02
Gliese 725 B	11.5	M3.5	V	18	43	+59	38	0.01
GX Andromedae	11.6	M1.5	V	00	18	+44	01	0.03
GQ Andromedae	11.6	M3.5	V	00	18	+44	01	0.003
ε Indi A	11.8	K5	V	22	03	−56	45	0.30
ε Indi B	11.8	T1.0	Brown dwarf	22	04	−56	46	—
ε Indi C	11.8	T6.0	Brown dwarf	22	04	−56	46	—
DX Cancri	11.8	M6.0	V	08	30	+26	47	0.0003
τ Ceti	11.9	G8.5	V	01	44	−15	57	0.67
GJ 1061	12.0	M5.0	V	03	36	−44	31	0.001

Note: These data were provided by the RECONS project, courtesy of Dr. Todd Henry (January, 2010). The luminosities are all total (bolometric) luminosities. The DA stellar types are white dwarfs. The coordinates are for the year 2000. The bolometric luminosity of the brown dwarfs is primarily in the infrared and has not been measured accurately yet.

Table F.2 *Twenty Brightest Stars*

Star	Constellation	RA h	RA m	Dec °	Dec ′	Distance (ly)	Spectral Type		Apparent Magnitude	Luminosity (L/L_{Sun})
Sirius	Canis Major	6	45	−16	42	8.6	A1	V	−1.46	26
Canopus	Carina	6	24	−52	41	313	F0	Ib-II	−0.72	13,000
α Centauri	Centaurus	14	40	−60	50	4.4	G2 K0	V V	−0.01 1.3	1.6 0.53
Arcturus	Boötes	14	16	+19	11	37	K2	III	−0.06	170
Vega	Lyra	18	37	+38	47	25	A0	V	0.04	60
Capella	Auriga	5	17	+46	00	42	G0 G8	III III	0.75 0.85	70 77
Rigel	Orion	5	15	−08	12	772	B8	Ia	0.14	70,000
Procyon	Canis Minor	7	39	+05	14	11.4	F5	IV–V	0.37	7.4
Betelgeuse	Orion	5	55	+07	24	427	M2	Iab	0.41	38,000
Achernar	Eridanus	1	38	−57	15	144	B5	V	0.51	3600
Hadar	Centaurus	14	04	−60	22	525	B1	III	0.63	100,000
Altair	Aquila	19	51	+08	52	17	A7	IV–V	0.77	10.5
Acrux	Crux	12	27	−63	06	321	B1 B3	IV V	1.39 1.9	22,000 7500
Aldebaran	Taurus	4	36	+16	30	65	K5	III	0.86	350
Spica	Virgo	13	25	−11	09	260	B1	V	0.91	23,000
Antares	Scorpio	16	29	−26	26	604	M1	Ib	0.92	38,000
Pollux	Gemini	7	45	+28	01	34	K0	III	1.16	45
Fomalhaut	Piscis Austrinus	22	58	−29	37	25	A3	V	1.19	18
Deneb	Cygnus	20	41	+45	16	2500	A2	Ia	1.26	170,000
β Crucis	Crux	12	48	−59	40	352	B0.5	IV	1.28	37,000

Note: Three of the stars on this list, Capella, α Centauri, and Acrux, are binary systems with members of comparable brightness. They are counted as single stars because that is how they appear to the naked eye. All the luminosities given are total (bolometric) luminosities. The coordinates are for the year 2000.

G Galaxy Data

Table G.1 *Galaxies of the Local Group*

Galaxy Name	Distance (millions of ly)	Type[a]	RA h	RA m	Dec °	Dec ′	Luminosity (millions of L_{Sun})
Milky Way	—	Sbc	—	—	—	—	15,000
WLM	3.0	Irr	00	02	−15	30	50
IC 10	2.7	dIrr	00	20	+59	18	160
Cetus	2.5	dE	00	26	−11	02	0.72
NGC 147	2.4	dE	00	33	+48	30	131
And III	2.5	dE	00	35	+36	30	1.1
NGC 185	2.0	dE	00	39	+48	20	120
NGC 205	2.7	E	00	40	+41	41	370
And VIII	2.7	dE	00	42	+40	37	240
M32	2.6	E	00	43	+40	52	380
M31	2.5	Sb	00	43	+41	16	21,000
And I	2.6	dE	00	46	+38	00	4.7
SMC	0.19	Irr	00	53	−72	50	230
And IX	2.9	dE	00	52	+43	12	—
Sculptor	0.26	dE	01	00	−33	42	2.2
LGS 3	2.6	dIrr	01	04	+21	53	1.3
IC 1613	2.3	Irr	01	05	+02	08	64
And V	2.9	dE	01	10	+47	38	—
And II	1.7	dE	01	16	+33	26	2.4
M33	2.7	Sc	01	34	+30	40	2800
Phoenix	1.5	dIrr	01	51	−44	27	0.9
Fornax	0.45	dE	02	40	−34	27	15.5
EGB0427 + 63	4.3	dIrr	04	32	+63	36	9.1
LMC	0.16	Irr	05	24	−69	45	1300
Carina	0.33	dE	06	42	−50	58	0.4
Canis Major	0.025	dIrr	07	15	−28	00	—
Leo A	2.2	dIrr	09	59	+30	45	3.0
Sextans B	4.4	dIrr	10	00	+05	20	41
NGC 3109	4.1	Irr	10	03	−26	09	160
Antlia	4.0	dIrr	10	04	−27	19	1.7
Leo I	0.82	dE	10	08	+12	18	4.8
Sextans A	4.7	dIrr	10	11	−04	42	56
Sextans	0.28	dE	10	13	−01	37	0.5
Leo II	0.67	dE	11	13	+22	09	0.6
GR 8	5.2	dIrr	12	59	+14	13	3.4
Ursa Minor	0.22	dE	15	09	+67	13	0.3
Draco	2.7	dE	17	20	+57	55	0.3
Sagittarius	0.08	dE	18	55	−30	29	18
SagDIG	3.5	dIrr	19	30	−17	41	6.8
NGC 6822	1.6	Irr	19	45	−14	48	94
DDO 210	2.6	dIrr	20	47	−12	51	0.8
IC 5152	5.2	dIrr	22	03	−51	18	70
Tucana	2.9	dE	22	42	−64	25	0.5
UKS2323-326	4.3	dE	23	26	−32	23	5.2
And VII	2.6	dE	23	38	+50	35	—
Pegasus	3.1	dIrr	23	29	+14	45	12
And VI	2.8	dE	23	52	+24	36	—

[a]Types beginning with S are spiral galaxies classified according to Hubble's system (see Chapter 15). Type E galaxies are elliptical or spheroidal. Type Irr galaxies are irregular. The prefix d denotes a dwarf galaxy. This list is based on a list originally published by M. Mateo in 1998 and augmented by discoveries of Local Group galaxies made between 1998 and 2005.

Table G.2 *Nearby Galaxies in the Messier Catalog*[a, b]

Galaxy Name (M / NGC)[c]	RA h	RA m	Dec °	Dec '	RV_{hel}[d]	RV_{gal}[e]	Type[f]	Nickname
M31 / NGC 224	00	43	+ 41	16	− 300 ± 4	− 122	Spiral	Andromeda
M32 / NGC 221	00	43	+ 40	52	− 145 ± 2	32	Elliptical	
M33 / NGC 598	01	34	+ 30	40	− 179 ± 3	− 44	Spiral	Triangulum
M49 / NGC 4472	12	30	+ 08	00	997 ± 7	929	Elliptical/ Lenticular/Seyfert	
M51 / NGC 5194	13	30	+ 47	12	463 ± 3	550	Spiral/Interacting	Whirlpool
M58 / NGC 4579	12	38	+ 11	49	1519 ± 6	1468	Spiral/Seyfert	
M59 / NGC 4621	12	42	+ 11	39	410 ± 6	361	Elliptical	
M60 / NGC 4649	12	44	+ 11	33	1117 ± 6	1068	Elliptical	
M61 / NGC 4303	12	22	+ 04	28	1566 ± 2	1483	Spiral/Seyfert	
M63 / NGC 5055	13	16	+ 42	02	504 ± 4	570	Spiral	Sunflower
M64 / NGC 4826	12	57	+ 21	41	408 ± 4	400	Spiral/Seyfert	Black Eye
M65 / NGC 3623	11	19	+ 13	06	807 ± 3	723	Spiral	
M66 / NGC 3627	11	20	+ 12	59	727 ± 3	643	Spiral/Seyfert	
M74 / NGC 628	01	37	+ 15	47	657 ± 1	754	Spiral	
M77 / NGC 1068	02	43	− 00	01	1137 ± 3	1146	Spiral/Seyfert	
M81 / NGC 3031	09	56	+ 69	04	−34 ± 4	73	Spiral/Seyfert	
M82 / NGC 3034	09	56	+ 69	41	203 ± 4	312	Irregular/Starburst	
M83 / NGC 5236	13	37	− 29	52	516 ± 4	385	Spiral/Starburst	
M84 / NGC 4374	12	25	+ 12	53	1060 ± 6	1005	Elliptical	
M85 / NGC 4382	12	25	+ 18	11	729 ± 2	692	Spiral	
M86 / NGC 4406	12	26	+ 12	57	−244 ± 5	− 298	Elliptical/Lenticular	
M87 / NGC 4486	12	30	+ 12	23	1307 ± 7	1254	Elliptical/Central Dominant/Seyfert	Virgo A
M88 / NGC 4501	12	32	+ 14	25	2281 ± 3	2235	Spiral/Seyfert	
M89 / NGC 4552	12	36	+ 12	33	340 ± 4	290	Elliptical	
M90 / NGC 4569	12	37	+ 13	10	−235 ± 4	− 282	Spiral/Seyfert	
M91 / NGC 4548	12	35	+ 14	30	486 ± 4	442	Spiral/Seyfert	
M94 / NGC 4736	12	51	+ 41	07	308 ± 1	360	Spiral	
M95 / NGC 3351	10	44	+ 11	42	778 ± 4	677	Spiral/Starburst	
M96 / NGC 3368	10	47	+ 11	49	897 ± 4	797	Spiral/Seyfert	
M98 / NGC 4192	12	14	+ 14	54	−142 ± 4	− 195	Spiral/Seyfert	
M99 / NGC 4254	12	19	+ 14	25	2407 ± 3	2354	Spiral	
M100 / NGC 4321	12	23	+ 15	49	1571 ± 1	1525	Spiral	
M101 / NGC 5457	14	03	+ 54	21	241 ± 2	360	Spiral	
M104 / NGC 4594	12	40	− 11	37	1024 ± 5	904	Spiral/Seyfert	Sombrero
M105 / NGC 3379	10	48	+ 12	35	911 ± 2	814	Elliptical	
M106 / NGC 4258	12	19	+ 47	18	448 ± 3	507	Spiral/Seyfert	
M108 / NGC 3556	11	09	+ 55	57	695 ± 3	765	Spiral	
M109 / NGC 3992	11	55	+ 53	39	1048 ± 4	1121	Spiral	
M110 / NGC 205	00	38	+ 41	25	−241 ± 3	− 61	Elliptical	

[a]Galaxies identified in the catalog published by Charles Messier in 1781; these galaxies are relatively easy to observe with small telescopes.

[b]Data obtained from NED: NASA/IPAC Extragalactic Database (http://ned.ipac.caltech.edu). The original Messier list of galaxies was obtained from SED, and the list data were updated to 2001 and M102 was dropped.

[c]The galaxies are identified by their Messier number (M followed by a number) and NGC number, which comes from the *New General Catalog* published in 1888.

[d]Radial velocity in kilometers per second, with respect to the Sun (heliocentric). Positive values mean motion away from the Sun; negative values are toward the Sun.

[e]Radial velocity in kilometers per second, with respect to the Milky Way Galaxy, calculated from the RV_{hel} values with a correction for the Sun's motion around the galactic center.

[f]Galaxies are first listed by their primary type (spiral, elliptical, or irregular) and then by any other special categories that apply (see Chapter 15).

Table G.3 *Nearby, X-Ray Bright Clusters of Galaxies*

Cluster Name	Redshift	Distance[a] (billions of ly)	Temperature of Intracluster Medium (millions of K)	Average Orbital Velocity of Galaxies[b] (km/s)	Cluster Mass[c] ($10^{15} M_{Sun}$)
Abell 2142	0.0907	1.26	101. ± 2	1132 ± 110	1.6
Abell 2029	0.0766	1.07	100. ± 3	1164 ± 98	1.5
Abell 401	0.0737	1.03	95.2 ± 5	1152 ± 86	1.4
Coma	0.0233	0.32	95.1 ± 1	821 ± 49	1.4
Abell 754	0.0539	0.75	93.3 ± 3	662 ± 77	1.4
Abell 2256	0.0589	0.82	87.0 ± 2	1348 ± 86	1.4
Abell 399	0.0718	1.00	81.7 ± 7	1116 ± 89	1.1
Abell 3571	0.0395	0.55	81.1 ± 3	1045 ± 109	1.1
Abell 478	0.0882	1.23	78.9 ± 2	904 ± 281	1.1
Abell 3667	0.0566	0.79	78.5 ± 6	971 ± 62	1.1
Abell 3266	0.0599	0.84	78.2 ± 5	1107 ± 82	1.1
Abell 1651a	0.0846	1.18	73.1 ± 6	685 ± 129	0.96
Abell 85	0.0560	0.78	70.9 ± 2	969 ± 95	0.92
Abell 119	0.0438	0.61	65.6 ± 5	679 ± 106	0.81
Abell 3558	0.0480	0.67	65.3 ± 2	977 ± 39	0.81
Abell 1795	0.0632	0.88	62.9 ± 2	834 ± 85	0.77
Abell 2199	0.0314	0.44	52.7 ± 1	801 ± 92	0.59
Abell 2147	0.0353	0.49	51.1 ± 4	821 ± 68	0.56
Abell 3562	0.0478	0.67	45.7 ± 8	736 ± 49	0.48
Abell 496	0.0325	0.45	45.3 ± 1	687 ± 89	0.47
Centaurus	0.0103	0.14	42.2 ± 1	863 ± 34	0.42
Abell 1367	0.0213	0.30	41.3 ± 2	822 ± 69	0.41
Hydra	0.0126	0.18	38.0 ± 1	610 ± 52	0.36
C0336	0.0349	0.49	37.4 ± 1	650 ± 170	0.35
Virgo	0.0038	0.05	25.7 ± 0.5	632 ± 41	0.20

Note: This table lists the 25 brightest clusters of galaxies in the X-ray sky from a catalog by J. P. Henry (2000).

[a]Cluster distances were computed using a value for Hubble's constant of 21.5 km/s/million light-years.

[b]The average orbital velocities given in this column are the velocity component along our line of sight. This velocity should be multiplied by the square root of 2 to get the average orbital velocity.

[c]This column gives each cluster's mass within the largest radius at which the intracluster medium can be in gravitational equilibrium. Because our estimates of that radius depend on Hubble's constant, these masses are inversely proportional to Hubble's constant, which we have assumed to be 21.5 km/s/million light-years.

H The 88 Constellations

Constellation Locations

These two charts each show half of the celestial sphere in projection, so that you can use them to learn the approximate locations of the constellations. The grid lines are marked by the right ascension and declination.

Constellation Names (English Equivalent in Parentheses)

Andromeda (The Chained Princess)
Antlia (The Air Pump)
Apus (The Bird of Paradise)
Aquarius (The Water Bearer)
Aquila (The Eagle)
Ara (The Altar)
Aries (The Ram)
Auriga (The Charioteer)
Boötes (The Herdsman)
Caelum (The Chisel)
Camelopardalis (The Giraffe)
Cancer (The Crab)
Canes Venatici (The Hunting Dogs)
Canis Major (The Great Dog)
Canis Minor (The Little Dog)
Capricornus (The Sea Goat)
Carina (The Keel)
Cassiopeia (The Queen)
Centaurus (The Centaur)
Cepheus (The King)
Cetus (The Whale)
Chamaeleon (The Chameleon)
Circinus (The Drawing Compass)
Columba (The Dove)
Coma Berenices (Berenice's Hair)
Corona Australis (The Southern Crown)
Corona Borealis (The Northern Crown)
Corvus (The Crow)
Crater (The Cup)
Crux (The Southern Cross)
Cygnus (The Swan)
Delphinus (The Dolphin)
Dorado (The Goldfish)
Draco (The Dragon)
Equuleus (The Little Horse)
Eridanus (The River)
Fornax (The Furnace)
Gemini (The Twins)
Grus (The Crane)
Hercules
Horologium (The Clock)
Hydra (The Sea Serpent)
Hydrus (The Water Snake)
Indus (The Indian)
Lacerta (The Lizard)
Leo (The Lion)
Leo Minor (The Little Lion)
Lepus (The Hare)
Libra (The Scales)
Lupus (The Wolf)
Lynx (The Lynx)
Lyra (The Lyre)
Mensa (The Table)
Microscopium (The Microscope)
Monoceros (The Unicorn)
Musca (The Fly)
Norma (The Level)
Octans (The Octant)
Ophiuchus (The Serpent Bearer)
Orion (The Hunter)
Pavo (The Peacock)
Pegasus (The Winged Horse)
Perseus (The Hero)
Phoenix (The Phoenix)
Pictor (The Painter's Easel)
Pisces (The Fish)
Piscis Austrinus (The Southern Fish)
Puppis (The Stern)
Pyxis (The Compass)
Reticulum (The Reticle)
Sagitta (The Arrow)
Sagittarius (The Archer)
Scorpius (The Scorpion)
Sculptor (The Sculptor)
Scutum (The Shield)
Serpens (The Serpent)
Sextans (The Sextant)
Taurus (The Bull)
Telescopium (The Telescope)
Triangulum (The Triangle)
Triangulum Australe (The Southern Triangle)
Tucana (The Toucan)
Ursa Major (The Great Bear)
Ursa Minor (The Little Bear)
Vela (The Sail)
Virgo (The Virgin)
Volans (The Flying Fish)
Vulpecula (The Fox)

All-Sky Constellation Map

This map of the entire sky shows the locations of all the constellations, in much the same way that a world map shows all of the countries on Earth. It does not use the usual celestial coordinate system of right ascension and declination, but instead is oriented so that the Milky Way Galaxy's center is at the center of the map and the Milky Way's disk (shown in shades of lighter blue) stretches from left to right across the map.

I Star Charts

How to use the star charts:

Check the times and dates under each chart to find the best one for you. Take it outdoors within an hour or so of the time listed for your date. Bring a dim flashlight to help you read it.

On each chart, the round outside edge represents the horizon all around you. Compass directions around the horizon are marked in yellow. Turn the chart around so that the edge marked with the direction you're facing (for example, north, southeast) is down. The stars above this horizon now match the stars you are facing. Ignore the rest until you turn to look in a different direction.

The center of the chart represents the sky overhead, so a star plotted on the chart halfway from the edge to the center can be found in the sky halfway from the horizon to straight up.

The charts are drawn for 40°N latitude (for example, Denver, New York, Madrid). If you live far south of there, stars in the southern part of your sky will appear higher than on the chart and stars in the north will be lower. If you live far north of there, the reverse is true.

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Use this chart January, February, and March.

Early January — 1 A.M.
Late January — Midnight

Early February — 11 P.M.
Late February — 10 P.M.

Early March — 9 P.M.
Late March — Dusk

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Use this chart April, May, and June.

Early April — 3 A.M.*	Early May — 1 A.M.*	Early June — 11 P.M.*
Late April — 2 A.M.*	Late May — Midnight*	Late June — Dusk

*Daylight Saving Time

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Use this chart July, August, and September.

Early July — 1 A.M.*	Early August — 11 P.M.*	Early September — 9 P.M.*
Late July — Midnight*	Late August — 10 P.M.*	Late September — Dusk

*Daylight Saving Time

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Use this chart October, November, and December.

Early October — 1 A.M.*	Early November — 10 P.M.	Early December — 8 P.M.
Late October — Midnight*	Late November — 9 P.M.	Late December — 7 P.M.

*Daylight Saving Time

J Solutions to Visual Skills Checks

Chapter 1

1. b
2. c
3. c
4. The nearest stars would not fit on Earth on this scale.

Chapter 2

1. B 2. D
3. A 4. C
5. d 6. d
7. c 8. c

Chapter 3

1. d 2. b
3. d 4. a
5. a 6. a
7. a

Chapter 4

1. b 2. d
3. a 4. d
5. c

Chapter 5

1. 5 2. 1
3. b 4. b
5. c

Chapter 6

1. About 4 days; about 50 meters per second
2. 1: d, 2: a, 3: c, 4: b
3. 1: c, 2: b, 3: d, 4: a
4. b

Chapter 7

1. a 2. c
3. b 4. b, c, a

Chapter 8

1. c 2. e
3. b 4. b

Chapter 9

1. About 5 km, though its unusual shape could lead to answers between 4 and 8 km
2. b
3. a
4. c
5. b

Chapter 10

1. d
2. Sunspots appear over a range of 40–50° North latitude to 40–50° South latitude.
3. Sunspots get closer to the equator during a sunspot cycle.

Chapter 11

1. b
2. d
3. c
4. Luminosity: about $10{,}000L_{\text{Sun}}$; lifetime: slightly longer than 10 million years
5. Luminosity: about $100L_{\text{Sun}}$; lifetime: slightly shorter than 1 billion years
6. Luminosity: about 30 L_{Sun}; lifetime: approximately 1 billion years

Chapter 12

1. Approximately $10L_{\text{Sun}}$
2. Approximately 3500 K
3. Approximately 10^4L_{Sun}
4. Approximately $10^{-4}L_{\text{Sun}}$

Chapter 13

1. b 2. d
3. b 4. c
5. d

Chapter 14

1. Brightest: white; lowest brightness: black/dark blue
2. White
3. Regions with strong radio emission are dark in the visible-light image.
4. Regions with strong radio emission are brighter in the infrared image than they are in the visible-light image.
5. c
6. yes

Chapter 15

1. Cepheids
2. Parallax
3. Approximately 100–10,000 light-years
4. White
5. Purple
6. Approximately 400,000 light-years
7. Approximately 20,000 light-years

Chapter 16

1. accelerating
2. accelerating
3. coasting
4. decelerating

Chapter 17

1. d 2. d
3. d 4. a

Chapter 18

1. g, f, b, e, d, c, a
2. b, a, c, d
3. a, c, d
4. d
5. c
6. c

Glossary

absolute magnitude A measure of an object's luminosity; defined to be the apparent magnitude the object would have if it were located exactly 10 parsecs away.

absolute zero The coldest possible temperature, which is 0 K.

absorption (of light) The process by which matter absorbs radiative energy.

absorption line spectrum A spectrum that contains absorption lines.

accelerating universe A universe in which a repulsive force (*see* cosmological constant) causes the expansion of the universe to accelerate with time. Its galaxies will recede from one another increasingly faster, and it will become cold and dark more quickly than a coasting universe.

acceleration The rate at which an object's velocity changes. Its standard units are m/s^2.

acceleration of gravity The acceleration of a falling object. On Earth, the acceleration of gravity, designated by g, is 9.8 m/s^2.

accretion The process by which small objects gather together to make larger objects.

accretion disk A rapidly rotating disk of material that gradually falls inward as it orbits a starlike object (e.g., white dwarf, neutron star, or black hole).

active galactic nuclei The unusually luminous centers of some galaxies, thought to be powered by accretion onto supermassive black holes. Quasars are the brightest type of active galactic nuclei; radio galaxies also contain active galactic nuclei.

active galaxy A term sometimes used to describe a galaxy that contains an *active galactic nucleus*.

adaptive optics A technique in which telescope mirrors flex rapidly to compensate for the bending of starlight caused by atmospheric turbulence.

Algol paradox A paradox concerning the binary star Algol, which contains a subgiant star that is less massive than its main-sequence companion.

altitude (above horizon) The angular distance between the horizon and an object in the sky.

amino acids The building blocks of proteins.

analemma The figure-8 path traced by the Sun over the course of a year when viewed at the same place and the same time each day; it represents the discrepancies between apparent and mean solar time.

Andromeda Galaxy (M31; the Great Galaxy in Andromeda) The nearest large spiral galaxy to the Milky Way.

angular momentum Momentum attributable to rotation or revolution. The angular momentum of an object moving in a circle of radius r is the product $m \times v \times r$.

angular resolution (of a telescope) The smallest angular separation that two pointlike objects can have and still be seen as distinct points of light (rather than as a single point of light).

angular size (or **angular distance**) A measure of the angle formed by extending imaginary lines outward from our eyes to span an object (or the space between two objects).

annihilation *See* matter–antimatter annihilation.

annular solar eclipse A solar eclipse during which the Moon is directly in front of the Sun but its angular size is not large enough to fully block the Sun; thus, a ring (or *annulus*) of sunlight is still visible around the Moon's disk.

Antarctic Circle The circle on Earth with latitude 66.5°S.

antielectron The antimatter equivalent of an electron. It is identical to an electron in virtually all respects, except it has a positive rather than a negative electrical charge.

antimatter Any particle with the same mass as a particle of ordinary matter but whose other basic properties, such as electrical charge, are precisely opposite.

aphelion The point at which an object orbiting the Sun is farthest from the Sun.

apogee The point at which an object orbiting Earth is farthest from Earth.

apparent brightness The amount of light reaching us *per unit area* from a luminous object; often measured in units of watts/m^2.

apparent magnitude A measure of the apparent brightness of an object in the sky, based on the ancient system developed by Hipparchus.

apparent retrograde motion The apparent motion of a planet, as viewed from Earth, during the period of a few weeks or months when it moves westward relative to the stars in our sky.

apparent solar time Time measured by the actual position of the Sun in your local sky, defined so that noon is when the Sun is *on* the meridian.

arcminute (or **minute of arc**) 1/60 of 1°.

arcsecond (or **second of arc**) 1/60 of an arcminute, or 1/3600 of 1°.

Arctic Circle The circle on Earth with latitude 66.5°N.

asteroid A relatively small and rocky object that orbits a star; asteroids are officially considered part of a category known as "small solar system bodies."

asteroid belt The region of our solar system between the orbits of Mars and Jupiter in which asteroids are heavily concentrated.

astrobiology The study of life on Earth and beyond; it emphasizes research into questions of the origin of life, the conditions under which life can survive, and the search for life beyond Earth.

astrometric technique The detection of extrasolar planets through the side-to-side motion of a star caused by gravitational tugs from the planet.

astronomical unit (AU) The average distance (semimajor axis) of Earth from the Sun, which is about 150 million km.

atmosphere A layer of gas that surrounds a planet or moon, usually very thin compared to the size of the object.

atmospheric pressure The surface pressure resulting from the overlying weight of an atmosphere.

atmospheric structure The layering of a planetary atmosphere due to variations in temperature with altitude. For example, Earth's atmospheric structure from the ground up consists of the troposphere, stratosphere, thermosphere, and exosphere.

atomic hydrogen gas Gas composed mostly of hydrogen atoms, though in space it is generally mixed with helium and small amounts of other elements as well; it is the most common form of interstellar gas.

atomic mass number The combined number of protons and neutrons in an atom.

atomic number The number of protons in an atom.

atoms Consist of a nucleus made from protons and neutrons, surrounded by a cloud of electrons.

aurora Dancing lights in the sky caused by charged particles entering our atmosphere; called the *aurora borealis* in the Northern Hemisphere and the *aurora australis* in the Southern Hemisphere.

axis tilt (of a planet in our solar system) The amount by which a planet's axis is tilted with respect to a line perpendicular to the ecliptic plane.

azimuth (usually called **direction** in this book) Direction around the horizon from due north, measured clockwise in degrees. For example, the azimuth of due north is 0°, due east is 90°, due south is 180°, and due west is 270°.

bar The standard unit of pressure, approximately equal to Earth's atmospheric pressure at sea level.

barred spiral galaxies Spiral galaxies that have a straight bar of stars cutting across their centers.

baryonic matter Ordinary matter made from atoms (so called because the nuclei of atoms contain protons and neutrons, which are both baryons).

baryons Particles, including protons and neutrons, that are made from three quarks.

basalt A type of dark, high-density volcanic rock that is rich in iron and magnesium-based silicate minerals; it forms a runny (easy flowing) lava when molten.

belts (on a jovian planet) Dark bands of sinking air that encircle a jovian planet at a particular set of latitudes.

Big Bang The name given to the event thought to mark the birth of the universe.

Big Bang theory The scientific theory of the universe's earliest moments, stating that all the matter in our observable universe came into being at a single moment in time as an extremely hot, dense mixture of subatomic particles and radiation.

Big Crunch The name given to the event that would presumably end the universe if gravity ever reverses the universal expansion and the universe someday begins to collapse.

binary star system A star system that contains two stars.

biosphere The "layer" of life on Earth.

blackbody radiation *See* thermal radiation.

black hole A bottomless pit in spacetime. Nothing can escape from within a black hole, and we can never again detect or observe an object that falls into a black hole.

black smokers Structures around seafloor volcanic vents that support a wide variety of life.

BL Lac objects A class of active galactic nuclei that probably represent the centers of radio galaxies whose jets happen to be pointed directly at us.

blowout Ejection of the hot, gaseous contents of a superbubble when it grows so large that it bursts out of the cooler layer of gas filling the galaxy's disk.

blueshift A Doppler shift in which spectral features are shifted to shorter wavelengths, observed when an object is moving toward the observer.

bosons Particles, such as photons, to which the exclusion principle does not apply.

bound orbits Orbits on which an object travels repeatedly around another object; bound orbits are elliptical in shape.

brown dwarf An object too small to become an ordinary star because electron degeneracy pressure halts its gravitational collapse before fusion becomes self-sustaining; brown dwarfs have mass less than $0.08M_{\text{Sun}}$.

bubble (interstellar) An expanding shell of hot, ionized gas driven by stellar winds or supernovae, with very hot and very low density gas inside.

bulge (of a spiral galaxy) The central portion of a spiral galaxy that is roughly spherical (or football shaped) and bulges above and below the plane of the galactic disk.

Cambrian explosion The dramatic diversification of life on Earth that occurred between about 540 and 500 million years ago.

carbonate rock A carbon-rich rock, such as limestone, that forms underwater from chemical reactions between sediments and carbon dioxide. On Earth, most of the outgassed carbon dioxide currently resides in carbonate rocks.

carbon dioxide cycle (CO_2 cycle) The process that cycles carbon dioxide between Earth's atmosphere and surface rocks.

carbon stars Stars whose atmospheres are especially carbon-rich, thought to be near the ends of their lives; carbon stars are the primary sources of carbon in the universe.

Cassini division A large, dark gap in Saturn's rings, visible through small telescopes on Earth.

CCD (charge coupled device) A type of electronic light detector that has largely replaced photographic film in astronomical research.

celestial coordinates The coordinates of right ascension and declination that fix an object's position on the celestial sphere.

celestial equator (CE) The extension of Earth's equator onto the celestial sphere.

celestial navigation Navigation on the surface of the Earth accomplished by observations of the Sun and stars.

celestial sphere The imaginary sphere on which objects in the sky appear to reside when observed from Earth.

Celsius (temperature scale) The temperature scale commonly used in daily activity internationally, defined so that, on Earth's surface, water freezes at 0°C and boils at 100°C.

center of mass (of orbiting objects) The point at which two or more orbiting objects would balance if they were somehow connected; it is the point around which the orbiting objects actually orbit.

central dominant galaxy A giant elliptical galaxy found at the center of a dense cluster of galaxies, apparently formed by the merger of several individual galaxies.

Cepheid *See* Cepheid variable stars.

Cepheid variable stars A particularly luminous type of pulsating variable star that follows a period–luminosity relation and hence is very useful for measuring cosmic distances.

Chandrasekhar limit *See* white dwarf limit.

charged particle belts Zones in which ions and electrons accumulate and encircle a planet.

chemical enrichment The process by which the abundance of heavy elements (heavier than helium) in the interstellar medium gradually increases over time as these elements are produced by stars and released into space.

chemical potential energy Potential energy that can be released through chemical reactions; for example, food contains chemical potential energy that your body can convert to other forms of energy.

chondrites Another name for primitive meteorites. The name comes from the round chodrules within them. *Achondrites,* meaning "without chondrules," is another name for processed meteorites.

chromosphere The layer of the Sun's atmosphere below the corona; most of the Sun's ultraviolet light is emitted from this region, in which the temperature is about 10,000 K.

circulation cells (or **Hadley cells**) Large-scale cells (similar to convection cells) in a planet's atmosphere that transport heat between the equator and the poles.

circumpolar star A star that always remains above the horizon for a particular latitude.

climate The long-term average of weather.

close binary A binary star system in which the two stars are very close together.

closed universe A universe in which spacetime curves back on itself to the point where its overall shape is analogous to that of the surface of a sphere.

cluster of galaxies A collection of a few dozen or more galaxies bound together by gravity; smaller collections of galaxies are simply called *groups.*

cluster of stars A group of anywhere from several hundred to a million or so stars; star clusters come in two types—open clusters and globular clusters.

CNO cycle The cycle of reactions by which intermediate- and high-mass stars fuse hydrogen into helium.

coasting universe A universe that will keep expanding forever with little change in its rate of expansion; in the absence of a repulsive force (*see* cosmological constant), a coasting universe is one in which the actual mass density is *smaller* than the critical density.

coma (of a comet) The dusty atmosphere of a comet, created by sublimation of ices in the nucleus when the comet is near the Sun.

comet A relatively small, icy object that orbits a star. Like asteroids, comets are officially considered part of a category known as "small solar system bodies."

comparative planetology The study of the solar system by examining and understanding the similarities and differences among worlds.

compound (chemical) A substance made from molecules consisting of two or more atoms with different atomic numbers.

condensates Solid or liquid particles that condense from a cloud of gas.

condensation The formation of solid or liquid particles from a cloud of gas.

conduction (of energy) The process by which thermal energy is transferred by direct contact from warm material to cooler material.

conjunction (of a planet with the Sun) An event in which a planet and the Sun line up in our sky.

conservation of angular momentum (law of) The principle that, in the absence of net torque (twisting force), the total angular momentum of a system remains constant.

conservation of energy (law of) The principle that energy (including mass-energy) can be neither created nor destroyed, but can only change from one form to another.

conservation of momentum (law of) The principle that, in the absence of net force, the total momentum of a system remains constant.

constellation A region of the sky; 88 official constellations cover the celestial sphere.

continental crust The thicker lower-density crust that makes up Earth's continents. It is made when remelting of seafloor crust allows lower-density rock to separate and erupt to the surface. Continental crust ranges in age from very young to as old as about 4 billion years (or more).

continuous spectrum A spectrum (of light) that spans a broad range of wavelengths without interruption by emission or absorption lines.

convection The energy transport process in which warm material expands and rises while cooler material contracts and falls.

convection cell An individual small region of convecting material.

convection zone (of a star) A region in which energy is transported outward by convection.

Copernican revolution The dramatic change, initiated by Copernicus, that occurred when we learned that Earth is a planet orbiting the Sun rather than the center of the universe.

core (of a planet) The dense central region of a planet that has undergone differentiation.

core (of a star) The central region of a star, in which nuclear fusion can occur.

Coriolis effect The effect due to rotation that causes air or objects on a rotating surface or planet to deviate from straight-line trajectories.

corona (solar) The tenuous uppermost layer of the Sun's atmosphere; most of the Sun's X rays are emitted from this region, in which the temperature is about 1 million K.

coronal holes Regions of the corona that barely show up in X-ray images because they are nearly devoid of hot coronal gas.

coronal mass ejections Bursts of charged particles from the Sun's corona that travel outward into space.

cosmic microwave background The remnant radiation from the Big Bang, which we detect using radio telescopes sensitive to microwaves (which are short-wavelength radio waves).

cosmic rays Particles such as electrons, protons, and atomic nuclei that zip through interstellar space at close to the speed of light.

cosmological constant The name given to a term in Einstein's equations of general relativity. If it is not zero, then it represents a repulsive force or a type of energy (sometimes called *dark energy* or *quintessence*) that might cause the expansion of the universe to accelerate with time.

cosmological horizon The boundary of our observable universe, which is where the lookback time is equal to the age of the universe. Beyond this boundary in spacetime, we cannot see anything at all.

Cosmological Principle The idea that matter is distributed uniformly throughout the universe on very large scales, meaning that the universe has neither a center nor an edge.

cosmological redshift The redshift we see from distant galaxies, caused by the fact that expansion of the universe stretches all the photons within it to longer, redder wavelengths.

cosmology The study of the overall structure and evolution of the universe.

cosmos An alternative name for the universe.

crescent (phase) The phase of the Moon (or of a planet) in which just a small portion (less than half) of the visible face is illuminated by sunlight.

critical density The precise average density for the entire universe that marks the dividing line between a recollapsing universe and one that will expand forever.

critical universe A universe that will never collapse, but that expands more and more slowly as time progresses; in the absence of a repulsive force (*see* cosmological constant), a critical universe is one in which the average mass density *equals* the critical density.

crust (of a planet) The low-density surface layer of a planet that has undergone differentiation.

curvature of spacetime A change in the geometry of space that is produced in the vicinity of a massive object and is responsible for the force we call gravity. The overall geometry of the universe may also be curved, depending on its overall mass-energy content.

cycles per second Units of frequency for a wave; describes the number of peaks (or troughs) of a wave that pass by a given point each second. Equivalent to *hertz.*

dark energy Name sometimes given to energy that could be causing the expansion of the universe to accelerate. *See* cosmological constant.

dark matter Matter that we infer to exist from its gravitational effects but from which we have not detected any light; dark matter apparently dominates the total mass of the universe.

daylight saving time Standard time plus 1 hour, so that the Sun appears on the meridian around 1 p.m. rather than around noon.

decay (radioactive) *See* radioactive decay.

declination (dec) Analogous to latitude, but on the celestial sphere; it is the angular north-south distance between the celestial equator and a location on the celestial sphere.

deferent The large circle upon which a planet follows its circle-upon-circle path around Earth in the (Earth-centered) Ptolemaic model of the universe. *See also* epicycle.

degeneracy pressure A type of pressure unrelated to an object's temperature, which arises when electrons (electron degeneracy pressure) or neutrons (neutron degeneracy pressure) are packed so tightly that the exclusion and uncertainty principles come into play.

degenerate object An object, such as a brown dwarf, white dwarf, or neutron star, in which degeneracy pressure is the primary pressure pushing back against gravity.

density (mass) The amount of mass per unit volume of an object. The average density of any object can be found by dividing its mass by its volume. Standard metric units are kilograms per cubic meter, but in astronomy density is more commonly stated in units of grams per cubic centimeter.

deuterium A form of hydrogen in which the nucleus contains a proton and a neutron, rather than only a proton (as is the case for most hydrogen nuclei).

differential rotation Rotation in which the equator of an object rotates at a different rate than the poles.

differentiation The process by which gravity separates materials according to density, with high-density materials sinking and low-density materials rising.

diffraction grating A finely etched surface that can split light into a spectrum.

diffraction limit The angular resolution that a telescope could achieve if it were limited only by the interference of light waves; it is smaller (i.e., better angular resolution) for larger telescopes.

dimension (mathematical) Describes the number of independent directions in which movement is possible; for example, the surface of Earth is two-dimensional because only two independent directions of motion are possible (north-south and east-west).

direction (in local sky) One of the two coordinates (the other is altitude) needed to pinpoint an object in the local sky. It is the direction, such as north, south, east, or west, in which you must face to see the object. *See also* azimuth.

disk (of a galaxy) The portion of a spiral galaxy that looks like a disk and contains an interstellar medium with cool gas and dust; stars of many ages are found in the disk.

disk population The stars that orbit within the disk of a spiral galaxy; sometimes called *Population I.*

DNA (deoxyribonucleic acid) The molecule that represents the genetic material of life on Earth.

Doppler effect (shift) The effect that shifts the wavelengths of spectral features in objects that are moving toward or away from the observer.

Doppler technique The detection of extrasolar planets through the motion of a star toward and away from the observer caused by gravitational tugs from the planet.

double shell–burning star A star that is fusing helium into carbon in a shell around an inert carbon core and is fusing hydrogen into helium in a shell at the top of the helium layer.

down quark One of the two quark types (the other is the up quark) found in ordinary protons and neutrons. It has a charge of $-\frac{1}{3}$.

Drake equation An equation that lays out the factors that play a role in determining the number of communicating civilizations in our galaxy.

dust (or **dust grains**) Tiny solid flecks of material; in astronomy, we often discuss interplanetary dust (found within a star system) or interstellar dust (found between the stars in a galaxy).

dust tail (of a comet) One of two tails seen when a comet passes near the Sun (the other is the plasma tail). It is composed of small solid particles pushed away from the Sun by the radiation pressure of sunlight.

dwarf elliptical galaxy A small elliptical galaxy with less than about a billion stars.

dwarf galaxies Relatively small galaxies, consisting of less than about 10 billion stars.

dwarf planet An object that orbits the Sun and is massive enough for its gravity to have made it nearly round in shape, but that does not qualify as an official planet because it has not cleared its orbital neighborhood. The dwarf planets of our solar system include the asteroid Ceres and the Kuiper belt objects Pluto, Eris, Haumea, and Makemake.

Earth-orbiters (spacecraft) Spacecraft designed to study Earth or the universe from Earth orbit.

eccentricity A measure of how much an ellipse deviates from a perfect circle; defined as the center-to-focus distance divided by the length of the semimajor axis.

eclipse An event in which one astronomical object casts a shadow on another or crosses our line of sight to the other object.

eclipse seasons Periods during which lunar and solar eclipses can occur because the nodes of the Moon's orbit are aligned with Earth and the Sun.

eclipsing binary A binary star system in which the two stars happen to be orbiting in the plane of our line of sight, so that each star will periodically eclipse the other.

ecliptic The Sun's apparent annual path among the constellations.

ecliptic plane The plane of Earth's orbit around the Sun.

ejecta (from an impact) Debris ejected by the blast of an impact.

electrical charge A fundamental property of matter that is described by its amount and as either positive or negative; more technically, a measure of how a particle responds to the electromagnetic force.

electromagnetic field An abstract concept used to describe how a charged particle would affect other charged particles at a distance.

electromagnetic radiation Another name for light of all types, from radio waves through gamma rays.

electromagnetic spectrum The complete spectrum of light, including radio waves, infrared light, visible light, ultraviolet light, X rays, and gamma rays.

electromagnetic wave A synonym for *light*, which consists of waves of electric and magnetic fields.

electromagnetism (or **electromagnetic force**) One of the four fundamental forces; it is the force that dominates atomic and molecular interactions.

electron degeneracy pressure Degeneracy pressure exerted by electrons, as in brown dwarfs and white dwarfs.

electrons Fundamental particles with negative electric charge; the distribution of electrons in an atom gives the atom its size.

electron-volt (eV) A unit of energy equivalent to 1.60×10^{-19} joule.

electroweak era The era of the universe during which only three forces operated (gravity, strong force, and electroweak force), lasting from 10^{-38} second to 10^{-10} second after the Big Bang.

electroweak force The force that exists at high energies when the electromagnetic force and the weak force exist as a single force.

element (chemical) A substance made from individual atoms of a particular atomic number.

ellipse A type of oval that happens to be the shape of bound orbits. An ellipse can be drawn by moving a pencil along a string whose ends are tied to two tacks; the locations of the tacks are the *foci* (singular: *focus*) of the ellipse.

elliptical galaxies Galaxies that appear rounded in shape, often longer in one direction, like a football. They have no disks and contain very little cool gas and dust compared to spiral galaxies, though they often contain very hot, ionized gas.

elongation (greatest) For Mercury or Venus, the point at which it appears farthest from the Sun in our sky.

emission (of light) The process by which matter emits energy in the form of light.

emission line spectrum A spectrum that contains emission lines.

emission nebula Another name for an ionization nebula. *See* ionization nebula.

energy Broadly speaking, what can make matter move. The three basic types of energy are kinetic, potential, and radiative.

energy balance (in a star) The balance between the rate at which fusion releases energy in the star's core and the rate at which the star's surface radiates this energy into space.

epicycle The small circle upon which a planet moves while simultaneously going around a larger circle (the *deferent*) around Earth in the (Earth-centered) Ptolemaic model of the universe.

equation of time An equation describing the discrepancies between apparent and mean solar time.

equinox *See* fall equinox *and* spring equinox.

equivalence principle The fundamental starting point for general relativity, which states that the effects of gravity are exactly equivalent to the effects of acceleration.

era of atoms The era of the universe lasting from about 500,000 years to about 1 billion years after the Big Bang, during which it was cool enough for neutral atoms to form.

era of galaxies The present era of the universe, which began with the formation of galaxies when the universe was about 1 billion years old.

era of nuclei The era of the universe lasting from about 3 minutes to about 380,000 years after the Big Bang, during which matter in the universe was fully ionized and opaque to light. The cosmic background radiation was released at the end of this era.

era of nucleosynthesis The era of the universe lasting from about 0.001 second to about 3 minutes after the Big Bang, by the end of which virtually all of the neutrons and about one-seventh of the protons in the universe had fused into helium.

erosion The wearing down or building up of geological features by wind, water, ice, and other phenomena of planetary weather.

eruption The process of releasing hot lava on the planet's surface.

escape velocity The speed necessary for an object to completely escape the gravity of a large body such as a moon, planet, or star.

evaporation The process by which atoms or molecules escape into the gas phase from a liquid.

event Any particular point along a worldline; all observers will agree on the reality of an event but may disagree about its time and location.

event horizon The boundary that marks the "point of no return" between a black hole and the outside universe; events that occur within the event horizon can have no influence on our observable universe.

evolution (biological) The gradual change in populations of living organisms responsible for transforming life on Earth from its primitive origins to the great diversity of life today.

exchange particle A type of subatomic particle that transmits one of the four fundamental forces; according to the standard model of physics, these particles are always exchanged whenever two objects interact through a force.

excited state (of an atom) Any arrangement of electrons in an atom that has more energy than the ground state.

exclusion principle The law of quantum mechanics that states that two fermions cannot occupy the same quantum state at the same time.

exosphere The hot, outer layer of an atmosphere, where the atmosphere "fades away" to space.

expansion (of the universe) The idea that the space between galaxies or clusters of galaxies is growing with time.

exposure time The amount of time during which light is collected to make a single image.

extrasolar planet A planet orbiting a star other than our Sun.

extremophiles Living organisms that are adapted to conditions that are "extreme" by human standards, such as very high or low temperature or a high level of salinity or radiation.

Fahrenheit (temperature scale) The temperature scale commonly used in daily activity in the

United States; defined so that, on Earth's surface, water freezes at 32°F and boils at 212°F.

fall (September) equinox Refers both to the point in Virgo on the celestial sphere where the ecliptic crosses the celestial equator and to the moment in time when the Sun appears at that point each year (around September 21).

false-color image An image displayed in colors that are *not* the true, visible-light colors of an object.

fault (geological) A place where rocks slip sideways relative to one another.

feedback processes Processes in which a small change in some property (such as temperature) leads to changes in other properties that either amplify or diminish the original small change.

fermions Particles, such as electrons, neutrons, and protons, that obey the exclusion principle.

Fermi's paradox The question posed by Enrico Fermi about extraterrestrial intelligence—"So where is everybody?"—which asks why we have not observed other civilizations even though simple arguments would suggest that some ought to have spread throughout the galaxy by now.

field An abstract concept used to describe how a particle would interact with a force. For example, the idea of a gravitational field describes how a particle would react to the local strength of gravity, and the idea of an electromagnetic field describes how a charged particle would respond to forces from other charged particles.

filter (for light) A material that transmits only particular wavelengths of light.

fireball A particularly bright meteor.

first-quarter (phase) The phase of the Moon that occurs one-quarter of the way through each cycle of phases, in which precisely half of the visible face is illuminated by sunlight.

fission The process by which one atomic nucleus breaks into two smaller nuclei. It releases energy if the two smaller nuclei together are less massive than the original nucleus.

flare star A small, spectral type M star that displays particularly strong flares on its surface.

flat (or **Euclidean**) **geometry** The type of geometry in which the rules of geometry for a flat plane hold, such as that the shortest distance between two points is a straight line and that the sum of the angles in a triangle is 180°.

flat universe A universe in which the overall geometry of spacetime is flat (Euclidean), as would be the case if the density of the universe was equal to the critical density.

flybys (spacecraft) Spacecraft that fly past a target object (such as a planet), usually just once, as opposed to entering a bound orbit of the object.

focal plane The place where an image created by a lens or mirror is in focus.

foci Plural of *focus.*

focus (of a lens or mirror) The point at which rays of light that were initially parallel (such as those from a distant star) converge.

focus (of an ellipse) One of two special points within an ellipse that lie along the major axis; these are the points around which we could stretch a pencil and string to draw an ellipse. When one object orbits a second object, the second object lies at one focus of the orbit.

force Anything that can cause a change in momentum.

formation properties (of planets) In this book, for the purpose of understanding geological processes, planets are defined to be born with four formation properties: size (mass and radius), distance from the Sun, composition, and rotation rate.

fossil Any relic of an organism that lived and died long ago.

frame of reference *See* reference frame.

free-fall The condition in which an object is falling without resistance; objects are weightless when in free-fall.

free-float frame A frame of reference in which all objects are weightless and hence float freely.

frequency The rate at which peaks of a wave pass by a point, measured in units of 1/s, often called *cycles per second* or *hertz.*

frost line The boundary in the solar nebula beyond which ices could condense; only metals and rocks could condense within the frost line.

fundamental forces There are four known fundamental forces in nature: gravity, the electromagnetic force, the strong force, and the weak force.

fundamental particles Subatomic particles that cannot be divided into anything smaller.

fusion The process by which two atomic nuclei fuse together to make a single, more massive nucleus. It releases energy if the final nucleus is less massive than the two nuclei that went into the reaction.

galactic cannibalism The term sometimes used to describe the process by which large galaxies merge with other galaxies in collisions. *Central dominant galaxies* are products of galactic cannibalism.

galactic fountain A model for the cycling of gas in the Milky Way Galaxy in which fountains of hot, ionized gas rise from the disk into the halo and then cool and form clouds as they sink back into the disk.

galactic wind A wind of low-density but extremely hot gas flowing out from a starburst galaxy, created by the combined energy of many supernovae.

galaxy A huge collection of anywhere from a few hundred million to more than a trillion stars, all bound together by gravity.

galaxy cluster *See* cluster of galaxies.

galaxy evolution The formation and development of galaxies.

Galilean moons The four moons of Jupiter that were discovered by Galileo: Io, Europa, Ganymede, and Callisto.

gamma-ray burst A sudden burst of gamma rays from deep space; such bursts apparently come from distant galaxies, but their precise mechanism is unknown.

gamma rays Light with very short wavelengths (and hence high frequencies)—shorter than those of X rays.

gap moons Tiny moons located within a gap in a planet's ring system. The gravity of a gap moon helps clear the gap.

gas phase The phase of matter in which atoms or molecules can move essentially independently of one another.

gas pressure The force (per unit area) pushing on any object due to surrounding gas. *See also* pressure.

general theory of relativity Einstein's generalization of his special theory of relativity so that the theory also applies when we consider effects of gravity or acceleration.

genetic code The "language" that living cells use to read the instructions chemically encoded in DNA.

geocentric model Any of the ancient Greek models that were used to predict planetary positions under the assumption that Earth lay in the center of the universe.

geocentric universe (ancient belief in) The idea that Earth is the center of the entire universe.

geological activity Processes that change a planet's surface long after formation, such as volcanism, tectonics, and erosion.

geological processes The four basic geological processes are impact cratering, volcanism, tectonics, and erosion.

geological time scale The time scale used by scientists to describe major eras in Earth's past.

geology The study of surface features (on a moon, planet, or asteroid) and the processes that create them.

geostationary satellite A satellite that appears to stay stationary in the sky as viewed from Earth's surface, because it orbits in the same time it takes Earth to rotate and orbits in Earth's equatorial plane.

geosynchronous satellite A satellite that orbits Earth in the same time it takes Earth to rotate (one sidereal day).

giant galaxies Galaxies that are unusually large, typically containing a trillion or more stars. Most giant galaxies are elliptical, and many contain multiple nuclei near their centers.

giant impact A collision between a forming planet and a very large planetesimal, such as is thought to have formed our Moon.

giant molecular cloud A very large cloud of cold, dense interstellar gas, typically containing up to a million solar masses worth of material. *See also* molecular clouds.

giants (luminosity class III) Stars that appear just below the supergiants on the H-R diagram because they are somewhat smaller in radius and lower in luminosity.

gibbous (phase) The phase of the Moon (or of a planet) in which more than half but less than all of the visible face is illuminated by sunlight.

global positioning system (GPS) A system of navigation by satellites orbiting Earth.

global warming An expected increase in Earth's global average temperature caused by human input of carbon dioxide and other greenhouse gases into the atmosphere.

global wind patterns (or **global circulation**) Wind patterns that remain fixed on a global scale, determined by the combination of surface heating and the planet's rotation.

globular cluster A spherically shaped cluster of up to a million or more stars; globular clusters are found primarily in the halos of galaxies and contain only very old stars.

gluons The exchange particles for the strong force.

grand unified theory (GUT) A theory that unifies three of the four fundamental forces—the strong force, the weak force, and the electromagnetic force (but not gravity)—in a single model.

granulation (on the Sun) The bubbling pattern visible in the photosphere, produced by the underlying convection.

gravitation (law of) *See* universal law of gravitation.

gravitational constant The experimentally measured constant G that appears in the law of universal gravitation:

$$G = 6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}$$

gravitational contraction The process in which gravity causes an object to contract, thereby converting gravitational potential energy into thermal energy.

gravitational encounter An encounter in which two (or more) objects pass near enough so that each can feel the effects of the other's gravity and they can therefore exchange energy.

gravitational equilibrium A state of balance in which the force of gravity pulling inward is precisely counteracted by pressure pushing outward.

gravitational lensing The magnification or distortion (into arcs, rings, or multiple images) of an image caused by light bending through a gravitational field, as predicted by Einstein's general theory of relativity.

gravitationally bound system Any system of objects, such as a star system or a galaxy, that is held together by gravity.

gravitational potential energy Energy that an object has by virtue of its position in a gravitational field; an object has more gravitational potential energy when it has a greater distance that it can potentially fall.

gravitational redshift A redshift caused by the fact that time runs slowly in gravitational fields.

gravitational time dilation The slowing of time that occurs in a gravitational field, as predicted by Einstein's general theory of relativity.

gravitational waves Waves, predicted by Einstein's general theory of relativity, that travel at the speed of light and transmit distortions of space through the universe. Although they have not yet been observed directly, we have strong indirect evidence that they exist.

gravitons The exchange particles for the force of gravity.

gravity One of the four fundamental forces; it is the force that dominates on large scales.

grazing incidence (in telescopes) Reflections in which light grazes a mirror surface and is deflected at a small angle; commonly used to focus high-energy ultraviolet light and X rays.

great circle A circle on the surface of a sphere whose center is at the center of the sphere.

greatest elongation *See* elongation (greatest).

Great Red Spot A large, high-pressure storm on Jupiter.

greenhouse effect The process by which greenhouse gases in an atmosphere make a planet's surface temperature warmer than it would be in the absence of an atmosphere.

greenhouse gases Gases, such as carbon dioxide, water vapor, and methane, that are particularly good absorbers of infrared light but are transparent to visible light.

Gregorian calendar Our modern calendar, introduced by Pope Gregory in 1582.

ground state (of an atom) The lowest possible energy state of the electrons in an atom.

group (of galaxies) A few to a few dozen galaxies bound together by gravity. *See also* cluster of galaxies.

GUT era The era of the universe during which only two forces operated (gravity and the grand-unified-theory, or GUT, force), lasting from 10^{-43} second to 10^{-38} second after the Big Bang.

GUT force The proposed force that exists at very high energies when the strong force, the weak force, and the electromagnetic force (but not gravity) all act as one.

H II region Another name for an ionization nebula. *See* ionization nebula.

habitable world A world with environmental conditions under which life could *potentially* arise or survive.

habitable zone The region around a star in which planets could potentially have surface temperatures at which liquid water could exist.

Hadley cells *See* circulation cells.

half-life The time it takes for half of the nuclei in a given quantity of a radioactive substance to decay.

halo (of a galaxy) The spherical region surrounding the disk of a spiral galaxy.

Hawking radiation Radiation predicted to arise from the evaporation of black holes.

heavy bombardment The period in the first few hundred million years after the solar system formed during which the tail end of planetary accretion created most of the craters found on ancient planetary surfaces.

heavy elements In astronomy, generally all elements *except* hydrogen and helium.

helium-burning star A star that is currently fusing helium into carbon in its core.

helium-capture reactions Fusion reactions that fuse a helium nucleus into some other nucleus; such reactions can fuse carbon into oxygen, oxygen into neon, neon into magnesium, and so on.

helium flash The event that marks the sudden onset of helium fusion in the previously inert helium core of a low-mass star.

helium fusion The fusion of three helium nuclei into one carbon nucleus; also called the *triple-alpha reaction.*

hertz (Hz) The standard unit of frequency for light waves; equivalent to units of 1/s.

Hertzsprung-Russell (H-R) diagram A graph plotting individual stars as points, with stellar luminosity on the vertical axis and spectral type (or surface temperature) on the horizontal axis.

high-mass stars Stars born with masses above about $8M_{\text{Sun}}$; these stars will end their lives by exploding as supernovae.

horizon A boundary that divides what we can see from what we cannot see.

horizontal branch The horizontal line of stars that represents helium-burning stars on an H-R diagram for a cluster of stars.

horoscope A predictive chart made by an astrologer; in scientific studies, horoscopes have never been found to have any validity as predictive tools.

hot Jupiter A class of planet that is Jupiter-like in size but orbits very close to it star, causing it to have a very high surface temperature.

hot spot (geological) A place within a plate of the lithosphere where a localized plume of hot mantle material rises.

hour angle (HA) The angle or time (measured in hours) since an object was last on the meridian in the local sky; defined to be 0 hours for objects that are on the meridian.

Hubble's constant A number that expresses the current rate of expansion of the universe; designated H_0, it is usually stated in units of km/s/Mpc. The reciprocal of Hubble's constant is the age the universe would have *if* the expansion rate had never changed.

Hubble's law Mathematical expression of the idea that more distant galaxies move away from us faster: $v = H_0 \times d$, where v is a galaxy's speed away from us, d is its distance, and H_0 is Hubble's constant.

hydrogen compounds Compounds that contain hydrogen and were common in the solar nebula, such as water (H_2O), ammonia (NH_3), and methane (CH_41).

hydrogen shell burning Hydrogen fusion that occurs in a shell surrounding a stellar core.

hydrosphere The "layer" of water on Earth consisting of oceans, lakes, rivers, ice caps, and other liquid water and ice.

hydrostatic equilibrium *See* gravitational equilibrium.

hyperbola The precise mathematical shape of one type of unbound orbit (the other is a parabola) allowed under the force of gravity; at great distances from the attracting object, a hyperbolic path looks like a straight line.

hypernova A term sometimes used to describe a supernova (explosion) of a star so massive that it leaves a black hole behind.

hyperspace Any space with more than three dimensions.

hypothesis A tentative model proposed to explain some set of observed facts, but which has not yet been rigorously tested and confirmed.

ice ages Periods of global cooling during which the polar caps, glaciers, and snow cover extend closer to the equator.

ices (in solar system theory) Materials that are solid only at low temperatures, such as the hydrogen compounds water, ammonia, and methane.

ideal gas law The law relating the pressure, temperature, and number density of particles in an ideal gas.

image A picture of an object made by focusing light.

imaging (in astronomical research) The process of obtaining pictures of astronomical objects.

impact The collision of a small body (such as an asteroid or comet) with a larger object (such as a planet or moon).

impact basin A very large impact crater, often filled by a lava flow.

impact crater A bowl-shaped depression left by the impact of an object that strikes a planetary surface (as opposed to burning up in the atmosphere).

impact cratering The excavation of bowl-shaped depressions (*impact craters*) by asteroids or comets striking a planet's surface.

impactor The object responsible for an impact.

inflation (of the universe) A sudden and dramatic expansion of the universe thought to have occurred at the end of the GUT era.

infrared light Light with wavelengths that fall in the portion of the electromagnetic spectrum between radio waves and visible light.

inner solar system Generally considered to encompass the region of our solar system out to about the orbit of Mars.

intensity (of light) A measure of the amount of energy coming from light of specific wavelength in the spectrum of an object.

interferometry A telescopic technique in which two or more telescopes are used in tandem to produce much better angular resolution than the telescopes could achieve individually.

intermediate-mass stars Stars born with masses between about $2M_{\text{Sun}}$ and $8M_{\text{Sun}}$; these stars end their lives by ejecting a planetary nebula and becoming a white dwarf.

interstellar cloud A cloud of gas and dust between the stars.

interstellar dust grains Tiny solid flecks of carbon and silicon minerals found in cool interstellar clouds; they resemble particles of smoke and form in the winds of red giant stars.

interstellar medium The gas and dust that fills the space between stars in a galaxy.

interstellar ramjet A hypothesized type of spaceship that uses a giant scoop to sweep up interstellar gas for use in a nuclear fusion engine.

interstellar reddening The change in the color of starlight as it passes through dusty gas. The light appears redder because dust grains absorb and scatter blue light more effectively than red light.

intracluster medium Hot, X-ray-emitting gas found between the galaxies within a cluster of galaxies.

inverse square law A law followed by any quantity that decreases with the square of the distance between two objects.

inverse square law for light The law stating that an object's apparent brightness depends on its actual luminosity and the inverse square of its distance from the observer:

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

inversion (atmospheric) A local weather condition in which air is colder near the surface than higher up in the troposphere—the opposite of the usual condition, in which the troposphere is warmer at the bottom.

ionization The process of stripping an electron from an atom.

ionization nebula A colorful, wispy cloud of gas that glows because neighboring hot stars irradiate it with ultraviolet photons that can ionize hydrogen atoms.

ionosphere A portion of the thermosphere in which ions are particularly common (because of ionization by X rays from the Sun).

ions Atoms with a positive or negative electrical charge.

Io torus A donut-shaped charged-particle belt around Jupiter that approximately traces Io's orbit.

irregular galaxies Galaxies that look neither spiral nor elliptical.

isotopes Forms of an element that have the same number of protons but different numbers of neutrons.

jets High-speed streams of gas ejected from an object into space.

joule The international unit of energy, equivalent to about 1/4000 of a Calorie.

jovian nebulae The clouds of gas that swirled around the jovian planets, from which the moons formed.

jovian planets Giant gaseous planets similar in overall composition to Jupiter.

Julian calendar The calendar introduced in 46 B.C. by Julius Caesar and used until the Gregorian calendar replaced it.

Kelvin (temperature scale) The most commonly used temperature scale in science, defined such that absolute zero is 0 K and water freezes at 273.15 K.

Kepler's first law Law stating that the orbit of each planet about the Sun is an ellipse with the Sun at one focus.

Kepler's laws of planetary motion Three laws discovered by Kepler that describe the motion of the planets around the Sun.

Kepler's second law The principle that, as a planet moves around its orbit, it sweeps out equal areas in equal times. This tells us that a planet moves faster when it is closer to the Sun (near perihelion) than when it is farther from the Sun (near aphelion) in its orbit.

Kepler's third law The principle that the square of a planet's orbital period is proportional to the cube of its average distance from the Sun (semimajor axis), which tells us that more distant planets move more slowly in their orbits; in its original form, written $p^2 = a^3$. *See also* Newton's version of Kepler's third law.

kinetic energy Energy of motion, given by the formula $\frac{1}{2}mv^2$.

Kirchhoff's laws A set of rules that summarizes the conditions under which objects produce thermal, absorption line, or emission line spectra. In brief: (1) An opaque object produces thermal radiation. (2) An absorption line spectrum occurs when thermal radiation passes through a thin gas that is cooler than the object emitting the thermal radiation. (3) An emission line spectrum occurs when we view a cloud of gas that is warmer than any background source of light.

Kirkwood gaps On a plot of asteroid semimajor axes, regions with few asteroids as a result of orbital resonances with Jupiter.

K–T event (or **impact**) The collision of an asteroid or comet 65 million years ago that caused the mass extinction best known for wiping out the dinosaurs. *K* and *T* stand for the geological layers above and below the event.

Kuiper belt The comet-rich region of our solar system that spans distances of about 30–100 AU from the Sun. Kuiper belt comets have orbits that lie fairly close to the plane of planetary orbits and travel around the Sun in the same direction as the planets.

Kuiper belt object Any object orbiting the Sun within the region of the Kuiper belt, although the term is most often used for relatively large objects. For example, Pluto and Eris are considered large Kuiper belt objects.

Large Magellanic Cloud One of two small, irregular galaxies (the other is the Small Magellanic Cloud) located about 150,000 light-years away; it probably orbits the Milky Way Galaxy.

large-scale structure (of the universe) Generally refers to the structure of the universe on size scales larger than that of clusters of galaxies.

latitude The angular north-south distance between Earth's equator and a location on Earth's surface.

leap year A calendar year with 366 rather than 365 days. Our current calendar (the Gregorian calendar) incorporates a leap year every 4 years (by adding February 29) except in century years that are not divisible by 400.

length contraction The effect in which you observe lengths to be shortened in reference frames moving relative to you.

lens (gravitational) *See* gravitational lensing.

lenticular galaxies Galaxies that look lens-shaped when seen edge-on, resembling spiral galaxies without arms. They tend to have less cool gas than normal spiral galaxies but more gas than elliptical galaxies.

leptons Fermions *not* made from quarks, such as electrons and neutrinos.

life track A track drawn on an H-R diagram to represent the changes in a star's surface temperature and luminosity during its life; also called an *evolutionary track.*

light-collecting area (of a telescope) The area of the primary mirror or lens that collects light in a telescope.

light curve A graph of an object's intensity against time.

light gases (in solar system theory) Hydrogen and helium, which never condense under solar nebula conditions.

light pollution Human-made light that hinders astronomical observations.

light-year (ly) The distance that light can travel in 1 year, which is 9.46 trillion km.

liquid phase The phase of matter in which atoms or molecules are held together but move relatively freely.

lithosphere The relatively rigid outer layer of a planet; generally encompasses the crust and the uppermost portion of the mantle.

Local Bubble (interstellar) The bubble of hot gas in which our Sun and other nearby stars apparently reside. *See also* bubble (interstellar).

Local Group The group of about 40 galaxies to which the Milky Way Galaxy belongs.

local sidereal time (LST) Sidereal time for a particular location, defined according to the position of the spring equinox in the local sky. More formally, the local sidereal time at any moment is defined to be the hour angle of the spring equinox.

local sky The sky as viewed from a particular location on Earth (or another solid object). Objects in the local sky are pinpointed by the coordinates of *altitude* and *direction* (or azimuth).

local solar neighborhood The portion of the Milky Way Galaxy that is located relatively close (within a few hundred to a couple thousand light-years) to our Sun.

Local Supercluster The supercluster of galaxies to which the Local Group belongs.

longitude The angular east-west distance between the prime meridian (which passes through Greenwich) and a location on Earth's surface.

lookback time The amount of time since the light we see from a distant object was emitted. If an object has a lookback time of 400 million years, we are seeing it as it looked 400 million years ago.

low-mass stars Stars born with masses less than about $2M_{\text{Sun}}$; these stars end their lives by ejecting a planetary nebula and becoming a white dwarf.

luminosity The total power output of an object, usually measured in watts or in units of solar luminosities ($L_{\text{Sun}} = 3.8 \times 10^{26}$ watts).

luminosity class A category describing the region of the H-R diagram in which a star falls. Luminosity class I represents supergiants, III represents giants, and V represents main-sequence stars; luminosity classes II and IV are intermediate to the others.

lunar eclipse An event that occurs when the Moon passes through Earth's shadow, which can occur only at full moon. A lunar eclipse may be total, partial, or penumbral.

lunar maria The regions of the Moon that look smooth from Earth and actually are impact basins.

lunar month *See* synodic month.

lunar phase *See* phase (of the Moon or a planet).

MACHOs One possible form of dark matter in which the dark objects are relatively large, like planets or brown dwarfs; stands for *massive compact halo objects.*

magma Underground molten rock.

magnetic braking The process by which a star's rotation slows as its magnetic field transfers its angular momentum to the surrounding nebula.

magnetic field The region surrounding a magnet in which it can affect other magnets or charged particles.

magnetic field lines Lines that represent how the needles on a series of compasses would point if they were laid out in a magnetic field.

magnetosphere The region surrounding a planet in which charged particles are trapped by the planet's magnetic field.

magnitude system A system for describing stellar brightness by using numbers, called *magnitudes,* based on an ancient Greek way of describing the brightnesses of stars in the sky. This system uses *apparent magnitude* to describe a star's apparent brightness and *absolute magnitude* to describe a star's luminosity.

main sequence The prominent line of points (representing *main-sequence stars*) running from the upper left to the lower right on an H-R diagram.

main-sequence fitting A method for measuring the distance to a cluster of stars by comparing the apparent brightness of the cluster's main sequence with that of the standard main sequence.

main-sequence lifetime The length of time for which a star of a particular mass can shine by fusing hydrogen into helium in its core.

main-sequence stars (luminosity class V) Stars whose temperature and luminosity place them on the main sequence of the H-R diagram. Main-sequence stars are all releasing energy by fusing hydrogen into helium in their cores.

main-sequence turnoff point The point on a cluster's H-R diagram where its stars turn off from the main sequence; the age of the cluster is equal to the main-sequence lifetime of stars at the main-sequence turnoff point.

mantle (of a planet) The rocky layer that lies between a planet's core and crust.

Martian meteorites Meteorites found on Earth that are thought to have originated on Mars.

mass A measure of the amount of matter in an object.

mass-energy The potential energy of mass, which has an amount $E = mc^2$.

mass exchange (in close binary star systems) The process in which tidal forces cause matter to spill from one star to a companion star in a close binary system.

mass extinction An event in which a large fraction of the species living on Earth go extinct, such as the event in which the dinosaurs died out about 65 million years ago.

mass increase (in relativity) The effect in which an object moving past you seems to have a mass greater than its rest mass.

massive star supernova A supernova that occurs when a massive star dies, initiated by the catastrophic collapse of its iron core; often called a *Type II supernova.*

mass-to-light ratio The mass of an object divided by its luminosity, usually stated in units of solar masses per solar luminosity. Objects with high mass-to-light ratios must contain substantial quantities of dark matter.

matter–antimatter annihilation An event that occurs when a particle of matter and a particle of antimatter meet and convert all of their mass-energy to photons.

mean solar time Time measured by the average position of the Sun in your local sky over the course of the year.

meridian A half-circle extending from your horizon (altitude 0°) due south, through your zenith, to your horizon due north.

metallic hydrogen Hydrogen that is so compressed that the hydrogen atoms all share electrons and thereby take on properties of metals, such as conducting electricity. It occurs only under very high-pressure conditions, such as those found deep within Jupiter.

metals (in solar system theory) Elements, such as nickel, iron, and aluminum, that condense at fairly high temperatures.

meteor A flash of light caused when a particle from space burns up in our atmosphere.

meteorite A rock from space that lands on Earth.

meteor shower A period during which many more meteors than usual can be seen.

Metonic cycle The 19-year period, discovered by the Babylonian astronomer Meton, over which the lunar phases occur on the same dates.

microwaves Light with wavelengths in the range of micrometers to millimeters. Microwaves are generally considered to be a subset of the radio wave portion of the electromagnetic spectrum.

mid-ocean ridges Long ridges of undersea volcanoes on Earth, along which mantle material erupts onto the ocean floor and pushes apart the existing seafloor on either side. These ridges are essentially the source of new seafloor crust, which then makes its way along the ocean bottom for millions of years before returning to the mantle at a subduction zone.

Milankovitch cycles The cyclical changes in Earth's axis tilt and orbit that can change the climate and cause ice ages.

Milky Way Used both as the name of our galaxy and to refer to the band of light we see in the sky when we look into the plane of the Milky Way Galaxy.

millisecond pulsars Pulsars with rotation periods of a few thousandths of a second.

minor planets An alternative name for *asteroids.*

model (scientific) A representation of some aspect of nature that can be used to explain and predict real phenomena without invoking myth, magic, or the supernatural.

molecular bands The tightly bunched lines in an object's spectrum that are produced by molecules.

molecular cloud fragments (or **molecular cloud cores**) The densest regions of molecular clouds, which usually go on to form stars.

molecular clouds Cool, dense interstellar clouds in which the low temperatures allow hydrogen atoms to pair up into hydrogen molecules (H_2).

molecular dissociation The process by which a molecule splits into its component atoms.

molecule Technically, the smallest unit of a chemical element or compound; in this text, the term refers only to combinations of two or more atoms held together by chemical bonds.

momentum The product of an object's mass and velocity.

moon An object that orbits a planet.

moonlets Very small moons that orbit within the ring systems of jovian planets.

mutations Errors in the copying process when a living cell replicates itself.

natural selection The process by which mutations that make an organism better able to survive get passed on to future generations.

neap tides The lower-than-average tides on Earth that occur at first- and third-quarter moon, when the tidal forces from the Sun and Moon oppose each other.

nebula A cloud of gas in space, usually one that is glowing.

nebular capture The process by which icy planetesimals capture hydrogen and helium gas to form jovian planets.

nebular theory The detailed theory that describes how our solar system formed from a cloud of interstellar gas and dust.

net force The overall force to which an object responds; the net force is equal to the rate of change in the object's momentum, or equivalently to the object's mass × acceleration.

neutrino A type of fundamental particle that has extremely low mass and responds only to the weak force; neutrinos are leptons and come in three types—electron neutrinos, mu neutrinos, and tau neutrinos.

neutron degeneracy pressure Degeneracy pressure exerted by neutrons, as in neutron stars.

neutrons Particles with no electrical charge found in atomic nuclei, built from three quarks.

neutron star The compact corpse of a high-mass star left over after a supernova; it typically contains a mass comparable to the mass of the Sun in a volume just a few kilometers in radius.

newton The standard unit of force in the metric system:

$$1 \text{ newton} = 1 \frac{\text{kg} \times \text{m}}{\text{s}^2}$$

Newton's first law of motion Principle that, in the absence of a net force, an object moves with constant velocity.

Newton's laws of motion Three basic laws that describe how objects respond to forces.

Newton's second law of motion Law stating how a net force affects an object's motion. Specifically, force = rate of change in momentum, or force = mass × acceleration.

Newton's third law of motion Principle that, for any force, there is always an equal and opposite reaction force.

Newton's universal law of gravitation *See* universal law of gravitation.

Newton's version of Kepler's third law A generalization of Kepler's third law used to calculate the masses of orbiting objects from measurements of orbital period and distance; usually written as

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

nodes (of Moon's orbit) The two points in the Moon's orbit where it crosses the ecliptic plane.

nonbaryonic matter Matter that is not part of the normal composition of atoms, such as neutrinos or the hypothetical WIMPs. (More technically, particles that are not made from three quarks.)

nonscience As defined in this book, any way of searching for knowledge that makes no claim to follow the scientific method, such as seeking knowledge through intuition, tradition, or faith.

north celestial pole (NCP) The point on the celestial sphere directly above Earth's North Pole.

nova The dramatic brightening of a star that lasts for a few weeks and then subsides; it occurs when a burst of hydrogen fusion ignites in a shell on the surface of an accreting white dwarf in a binary star system.

nuclear fission The process in which a larger nucleus splits into two (or more) smaller particles.

nuclear fusion The process in which two (or more) smaller nuclei slam together and make one larger nucleus.

nucleus (of a comet) The solid portion of a comet—the only portion that exists when the comet is far from the Sun.

nucleus (of an atom) The compact center of an atom made from protons and neutrons.

observable universe The portion of the entire universe that, at least in principle, can be seen from Earth.

Occam's razor A principle often used in science, holding that scientists should prefer the simpler of two models that agree equally well with observations; named after the medieval scholar William of Occam (1285–1349).

Olbers' paradox A paradox pointing out that if the universe were infinite in both age and size (with stars found throughout the universe), then the sky would not be dark at night.

Oort cloud A huge, spherical region centered on the Sun, extending perhaps halfway to the nearest stars, in which trillions of comets orbit the Sun with random inclinations, orbital directions, and eccentricities.

opacity A measure of how much light a material absorbs compared to how much it transmits; materials with higher opacity absorb more light.

opaque Describes a material that absorbs light.

open cluster A cluster of up to several thousand stars; open clusters are found only in the disks of galaxies and often contain young stars.

open universe A universe in which spacetime has an overall shape analogous to the surface of a saddle.

opposition The point at which a planet appears opposite the Sun in our sky.

optical quality The ability of a lens, mirror, or telescope to obtain clear and properly focused images.

orbit The path followed by a celestial body because of gravity; an orbit may be *bound* (elliptical) or *unbound* (parabolic or hyperbolic).

orbital energy The sum of an orbiting object's kinetic and gravitational potential energies.

orbital resonance A situation in which one object's orbital period is a simple ratio of another object's period, such as 1/2, 1/4, or 5/3. In such cases, the two objects periodically line up with each other, and the extra gravitational attractions at these times can affect the objects' orbits.

orbital velocity law A variation on Newton's version of Kepler's third law that allows us to use a star's orbital speed and distance from the galactic center to determine the total mass of the galaxy contained *within* the star's orbit; mathematically,

$$M_r = \frac{r \times v^2}{G}$$

where M_r is the mass contained within the star's orbit, r is the star's distance from the galactic center, v is the star's orbital velocity, and G is the gravitational constant.

orbiters (of other worlds) Spacecraft that go into orbit of another world for long-term study.

outer solar system Generally considered to encompass the region of our solar system beginning at about the orbit of Jupiter.

outgassing The process of releasing gases from a planetary interior, usually through volcanic eruptions.

oxidation Chemical reactions, often with rocks on the surface of a planet, that remove oxygen from the atmosphere.

ozone The molecule O_3, which is a particularly good absorber of ultraviolet light.

ozone depletion The decline in levels of atmospheric ozone found worldwide on Earth, especially in Antarctica, in recent years.

ozone hole A place where the concentration of ozone in the stratosphere is dramatically lower than is the norm.

pair production The process in which a concentration of energy spontaneously turns into a particle and its antiparticle.

parabola The precise mathematical shape of a special type of unbound orbit allowed under the force of gravity. If an object in a parabolic orbit loses only a tiny amount of energy, it will become bound.

paradigm (in science) A general pattern of thought that tends to shape scientific study during a particular time period.

paradox A situation that, at least at first, seems to violate common sense or contradict itself. Resolving paradoxes often leads to deeper understanding.

parallax The apparent shifting of an object against the background, due to viewing it from different positions. *See also* stellar parallax.

parallax angle Half of a star's annual back-and-forth shift due to stellar parallax; related to the star's distance according to the formula

$$\text{distance in parsecs} = \frac{1}{p}$$

where p is the parallax angle in arcseconds.

parsec (pc) The distance to an object with a parallax angle of 1 arcsecond; approximately equal to 3.26 light-years.

partial lunar eclipse A lunar eclipse during which the Moon becomes only partially covered by Earth's umbral shadow.

partial solar eclipse A solar eclipse during which the Sun becomes only partially blocked by the disk of the Moon.

particle accelerator A machine designed to accelerate subatomic particles to high speeds in order to create new particles or to test fundamental theories of physics.

particle era The era of the universe lasting from 10^{-10} second to 0.001 second after the Big Bang, during which subatomic particles were continually created and destroyed and ending when matter annihilated antimatter.

peculiar velocity (of a galaxy) The component of a galaxy's velocity relative to the Milky Way that deviates from the velocity expected by Hubble's law.

penumbra The lighter, outlying regions of a shadow.

penumbral lunar eclipse A lunar eclipse during which the Moon passes only within Earth's penumbral shadow and does not fall within the umbra.

perigee The point at which an object orbiting Earth is nearest to Earth.

perihelion The point at which an object orbiting the Sun is closest to the Sun.

period–luminosity relation The relation that describes how the luminosity of a Cepheid variable star is related to the period between peaks in its brightness; the longer the period, the more luminous the star.

phase (of matter) The state determined by the way in which atoms or molecules are held together; the common phases are solid, liquid, and gas.

phase (of the Moon or a planet) The state determined by the portion of the visible face of the Moon (or of a planet) that is illuminated by sunlight. For the Moon, the phases cycle through new, waxing crescent, first-quarter, waxing gibbous, full, waning gibbous, third-quarter, waning crescent, and back to new.

photon An individual particle of light, characterized by a wavelength and a frequency.

photosphere The visible surface of the Sun, where the temperature averages just under 6000 K.

pixel An individual "picture element" on a CCD.

Planck era The era of the universe prior to the Planck time.

Planck's constant A universal constant, abbreviated h, with a value of $h = 6.626 \times 10^{-34}$ joule $\times$ s.

Planck time The time when the universe was 10^{-43} second old, before which random energy fluctuations were so large that our current theories are powerless to describe what might have been happening.

planet A moderately large object that orbits a star and shines primarily by reflecting light from its star. More precisely, according to a definition approved in 2006, a planet is an object that (1) orbits a star (but is itself neither a star nor a moon); (2) is massive enough for its own gravity to give it a nearly round shape; and (3) has cleared the neighborhood around its orbit. Objects that meet the first two criteria but not the third, including Ceres, Pluto, and Eris, are designated *dwarf planets.*

planetary geology The extension of the study of Earth's surface and interior to apply to other solid bodies in the solar system, such as terrestrial planets and jovian planet moons.

planetary migration A process through which a planet can move from the orbit on which it is born to a different orbit that is closer to or farther from its star.

planetary nebula The glowing cloud of gas ejected from a low-mass star at the end of its life.

planetesimals The building blocks of planets, formed by accretion in the solar nebula.

plasma A gas consisting of ions and electrons.

plasma tail (of a comet) One of two tails seen when a comet passes near the Sun (the other is the dust tail). It is composed of ionized gas blown away from the Sun by the solar wind.

plates (on a planet) Pieces of a lithosphere that apparently float upon the denser mantle below.

plate tectonics The geological process in which plates are moved around by stresses in a planet's mantle.

polarization (of light) The property of light describing how the electric and magnetic fields of light waves are aligned; light is said to be *polarized* when all of the photons have their electric and magnetic fields aligned in some particular way.

Population I *See* disk population.

Population II *See* spheroidal population.

positron *See* antielectron.

potential energy Energy stored for later conversion into kinetic energy; includes gravitational potential energy, electrical potential energy, and chemical potential energy.

power The rate of energy usage, usually measured in watts (1 watt = 1 joule/s).

precession The gradual wobble of the axis of a rotating object around a vertical line.

precipitation Condensed atmospheric gases that fall to the surface in the form of rain, snow, or hail.

pressure The force (per unit area) pushing on an object. In astronomy, we are generally interested in pressure applied by surrounding gas (or plasma). Ordinarily, such pressure is related to the temperature of the gas (*see* thermal pressure). In objects such as white dwarfs and neutron stars, pressure may arise from a quantum effect (*see* degeneracy pressure). Light can also exert pressure (*see* radiation pressure).

primary mirror The large, light-collecting mirror of a reflecting telescope.

prime focus (of a reflecting telescope) The first point at which light focuses after bouncing off the primary mirror; located in front of the primary mirror.

prime meridian The meridian of longitude that passes through Greenwich, England; defined to be longitude 0°.

primitive meteorites Meteorites that formed at the same time as the solar system itself, about 4.6 billion years ago. Primitive meteorites from the inner asteroid belt are usually stony, and those from the outer belt are usually carbon-rich.

processed meteorites Meteorites that apparently once were part of a larger object that "processed" the original material of the solar nebula into another form. Processed meteorites can be rocky if chipped from the surface or mantle, or metallic if blasted from the core.

proper motion The motion of an object in the plane of the sky, perpendicular to our line of sight.

protogalactic cloud A huge, collapsing cloud of intergalactic gas from which an individual galaxy formed.

proton–proton chain The chain of reactions by which low-mass stars (including the Sun) fuse hydrogen into helium.

protons Particles found in atomic nuclei with positive electrical charge, built from three quarks.

protoplanetary disk A disk of material surrounding a young star (or protostar) that may eventually form planets.

protostar A forming star that has not yet reached the point where sustained fusion can occur in its core.

protostellar disk A disk of material surrounding a protostar; essentially the same as a protoplanetary

disk, but may not necessarily lead to planet formation.

protostellar wind The relatively strong wind from a protostar.

protosun The central object in the forming solar system that eventually became the Sun.

pseudoscience Something that purports to be science or may appear to be scientific but that does not adhere to the testing and verification requirements of the scientific method.

Ptolemaic model The geocentric model of the universe developed by Ptolemy in about 150 A.D.

pulsar A neutron star from which we see rapid pulses of radiation as it rotates.

pulsating variable stars Stars that grow alternately brighter and dimmer as their outer layers expand and contract in size.

quantum laws The laws that describe the behavior of particles on a very small scale; *see also* quantum mechanics.

quantum mechanics The branch of physics that deals with the very small, including molecules, atoms, and fundamental particles.

quantum state The complete description of the state of a subatomic particle, including its location, momentum, orbital angular momentum, and spin, to the extent allowed by the uncertainty principle.

quantum tunneling The process in which, thanks to the uncertainty principle, an electron or other subatomic particle appears on the other side of a barrier that it does not have the energy to overcome in a normal way.

quarks The building blocks of protons and neutrons; quarks are one of the two basic types of fermions (leptons are the other).

quasar The brightest type of active galactic nucleus.

radar mapping Imaging of a planet by bouncing radar waves off its surface, especially important for Venus and Titan, where thick clouds mask the surface.

radar ranging A method of measuring distances within the solar system by bouncing radio waves off planets.

radial motion The component of an object's motion directed toward or away from us.

radial velocity The portion of any object's total velocity that is directed toward or away from us. This part of the velocity is the only part that we can measure with the Doppler effect.

radiation pressure Pressure exerted by photons of light.

radiation zone (of a star) A region of the interior in which energy is transported primarily by radiative diffusion.

radiative diffusion The process by which photons gradually migrate from a hot region (such as the solar core) to a cooler region (such as the solar surface).

radiative energy Energy carried by light; the energy of a photon is Planck's constant times its frequency, or $h \times f$.

radioactive decay The spontaneous change of an atom into a different element, in which its nucleus breaks apart or a proton turns into an electron. It releases heat in a planet's interior.

radioactive element (or **radioactive isotope**) A substance whose nucleus tends to fall apart spontaneously.

radio galaxy A galaxy that emits unusually large quantities of radio waves; thought to contain an active galactic nucleus powered by a supermassive black hole.

radio lobes The huge regions of radio emission found on either side of radio galaxies. The lobes apparently contain plasma ejected by powerful jets from the galactic center.

radiometric dating The process of determining the age of a rock (i.e., the time since it solidified) by comparing the present amount of a radioactive substance to the amount of its decay product.

radio waves Light with very long wavelengths (and hence low frequencies)—longer than those of infrared light.

random walk A type of haphazard movement in which a particle or photon moves through a series of bounces, with each bounce sending it in a random direction.

recession velocity (of a galaxy) The speed at which a distant galaxy is moving away from us because of the expansion of the universe.

recollapsing universe A universe in which the collective gravity of all its matter eventually halts and reverses the expansion, causing the galaxies to come crashing back together and the universe to end in a fiery Big Crunch.

red giant A giant star that is red in color.

red-giant winds The relatively dense but slow winds from red giant stars.

redshift (Doppler) A Doppler shift in which spectral features are shifted to longer wavelengths, observed when an object is moving away from the observer.

reference frame (or **frame of reference**) What two people (or objects) share if they are *not* moving relative to one another.

reflecting telescope A telescope that uses mirrors to focus light.

reflection (of light) The process by which matter changes the direction of light.

reflection nebula A nebula that we see as a result of starlight reflected from interstellar dust grains. Reflection nebulae tend to have blue and black tints.

refracting telescope A telescope that uses lenses to focus light.

resonance *See* orbital resonance.

rest wavelength The wavelength of a spectral feature in the absence of any Doppler shift or gravitational redshift.

retrograde motion Motion that is backward compared to the norm. For example, we see Mars in apparent retrograde motion during the periods of time when it moves westward, rather than the more common eastward, relative to the stars.

revolution The orbital motion of one object around another.

right ascension (RA) Analogous to longitude, but on the celestial sphere; the angular east-west distance between the spring equinox and a location on the celestial sphere.

rings (planetary) The collections of numerous small particles orbiting a planet within its Roche tidal zone.

Roche tidal zone The region within two to three planetary radii (of any planet) in which the tidal forces tugging an object apart become comparable to the gravitational forces holding it together; planetary rings are always found within the Roche tidal zone.

rocks (in solar system theory) Materials common on the surface of Earth, such as silicon-based minerals, that are solid at temperatures and pressures found on Earth but typically melt or vaporize at temperatures of 500–1300 K.

rotation The spinning of an object around its axis.

rotation curve A graph that plots rotational (or orbital) velocity against distance from the center for any object or set of objects.

runaway greenhouse effect A positive feedback cycle in which heating caused by the greenhouse effect causes more greenhouse gases to enter the atmosphere, which further enhances the greenhouse effect.

saddle-shaped (or **hyperbolic**) **geometry** The type of geometry in which the rules—such as that two lines that begin parallel eventually diverge—are most easily visualized on a saddle-shaped surface.

Sagittarius Dwarf A small dwarf elliptical galaxy that is currently passing through the disk of the Milky Way Galaxy.

saros cycle The period over which the basic pattern of eclipses repeats, which is about 18 years $11\frac{1}{3}$ days.

satellite Any object orbiting another object.

scattered light Light that is reflected into random directions.

Schwarzschild radius A measure of the size of the event horizon of a black hole.

science The search for knowledge that can be used to explain or predict natural phenomena in a way that can be confirmed by rigorous observations or experiments.

scientific method An organized approach to explaining observed facts through science.

scientific theory A model of some aspect of nature that has been rigorously tested and has passed all tests to date.

seafloor crust On Earth, the thin, dense crust of basalt created by seafloor spreading.

seafloor spreading On Earth, the creation of new seafloor crust at mid-ocean ridges.

search for extraterrestrial intelligence (SETI) The name given to observing projects designed to search for signs of intelligent life beyond Earth.

secondary mirror A small mirror in a reflecting telescope, used to reflect light gathered by the primary mirror toward an eyepiece or instrument.

sedimentary rock A rock that formed from sediments created and deposited by erosional processes.

seismic waves Earthquake-induced vibrations that propagate through a planet.

selection effect (or **selection bias**) A type of bias that arises from the way in which objects of study are selected and that can lead to incorrect conclusions. For example, when you are counting animals in a jungle it is easiest to see brightly colored animals, which could mislead you into thinking that these animals are the most common.

semimajor axis Half the distance across the long axis of an ellipse; in this text, it is usually referred to as the *average* distance of an orbiting object, abbreviated *a* in the formula for Kepler's third law.

Seyfert galaxies The name given to a class of galaxies that are found relatively nearby and that have nuclei much like those of quasars, except that they are less luminous.

shepherd moons Tiny moons within a planet's ring system that help force particles into a narrow ring; a variation on *gap moons.*

shield volcano A shallow-sloped volcano made from the flow of low-viscosity basaltic lava.

shock wave A wave of pressure generated by gas moving faster than the speed of sound.

sidereal day The time of 23 hours 56 minutes 4.09 seconds between successive appearances of any particular star on the meridian; essentially, the true rotation period of Earth.

sidereal month The time required for the Moon to orbit Earth once (as measured against the stars); about $27\frac{1}{4}$ days.

sidereal period (of a planet) A planet's actual orbital period around the Sun.

sidereal time Time measured according to the position of stars in the sky rather than the position of the Sun in the sky. *See also* local sidereal time.

sidereal year The time required for Earth to complete exactly one orbit as measured against the stars; about 20 minutes longer than the tropical year on which our calendar is based.

silicate rock A silicon-rich rock.

singularity The place at the center of a black hole where, in principle, gravity crushes all matter to an infinitely tiny and dense point.

Small Magellanic Cloud One of two small, irregular galaxies (the other is the Large Magellanic Cloud) located about 150,000 light-years away; it probably orbits the Milky Way Galaxy.

small solar system body An asteroid, comet, or other object that orbits a star but is too small to qualify as a planet or dwarf planet.

snowball Earth Name given to a hypothesis suggesting that, some 600–700 million years ago, Earth experienced a period in which it became cold enough for glaciers to exist worldwide, even in equatorial regions.

solar activity Short-lived phenomena on the Sun, including the emergence and disappearance of individual sunspots, prominences, and flares; sometimes called *solar weather.*

solar circle The Sun's orbital path around the galaxy, which has a radius of about 28,000 light-years.

solar day 24 hours, which is the average time between appearances of the Sun on the meridian.

solar eclipse An event that occurs when the Moon's shadow falls on Earth, which can occur only at new moon. A solar eclipse may be total, partial, or annular.

solar flares Huge and sudden releases of energy on the solar surface, probably caused when energy stored in magnetic fields is suddenly released.

solar luminosity The luminosity of the Sun, which is approximately 4×10^{26} watts.

solar maximum The time during each sunspot cycle at which the number of sunspots is the greatest.

solar minimum The time during each sunspot cycle at which the number of sunspots is the smallest.

solar nebula The piece of interstellar cloud from which our own solar system formed.

solar neutrino problem The disagreement between the predicted and observed number of neutrinos coming from the Sun.

solar prominences Vaulted loops of hot gas that rise above the Sun's surface and follow magnetic field lines.

solar sail A large, highly reflective (and thin, to minimize mass) piece of material that can "sail" through space using pressure exerted by sunlight.

solar system (or **star system**) A star (sometimes more than one star) and all the objects that orbit it.

solar thermostat *See* stellar thermostat; the solar thermostat is the same idea applied to the Sun.

solar wind A stream of charged particles ejected from the Sun.

solid phase The phase of matter in which atoms or molecules are held rigidly in place.

solstice *See* summer solstice *and* winter solstice.

sound wave A wave of alternately rising and falling pressure.

south celestial pole (SCP) The point on the celestial sphere directly above Earth's South Pole.

spacetime The inseparable, four-dimensional combination of space and time.

spacetime diagram A graph that plots a spatial dimension on one axis and time on another axis.

special theory of relativity Einstein's theory that describes the effects of the fact that all motion is relative and that everyone always measures the same speed of light.

spectral lines Bright or dark lines that appear in an object's spectrum, which we can see when we pass the object's light through a prismlike device that spreads out the light like a rainbow.

spectral resolution The degree of detail that can be seen in a spectrum; the higher the spectral resolution, the more detail we can see.

spectral type A way of classifying a star by the lines that appear in its spectrum; it is related to surface temperature. The basic spectral types are designated by a letter (OBAFGKM, with O for the hottest stars and M for the coolest) and are subdivided with numbers from 0 through 9.

spectrograph An instrument used to record spectra.

spectroscopic binary A binary star system whose binary nature is revealed because we detect the spectral lines of one or both stars alternately becoming blueshifted and redshifted as the stars orbit each other.

spectroscopy (in astronomical research) The process of obtaining spectra from astronomical objects.

spectrum (of light) *See* electromagnetic spectrum.

speed The rate at which an object moves. Its units are distance divided by time, such as m/s or km/hr.

speed of light The speed at which light travels, which is about 300,000 km/s.

spherical geometry The type of geometry in which the rules—such as that lines that begin parallel eventually meet—are those that hold on the surface of a sphere.

spheroidal component (of a galaxy) The portion of any galaxy that is spherical (or football-like) in shape and contains very little cool gas; it generally contains only very old stars. Elliptical galaxies have only a spheroidal component, while spiral galaxies also have a disk component.

spheroidal galaxy Another name for an *elliptical galaxy.*

spheroidal population Stars that orbit within the spheroidal component of a galaxy; sometimes called *Population II.* Elliptical galaxies have only a spheroidal population (they lack a disk population), while spiral galaxies have spheroidal population stars in their bulges and halos.

spin (quantum) *See* spin angular momentum.

spin angular momentum The inherent angular momentum of a fundamental particle; often simply called *spin.*

spiral arms The bright, prominent arms, usually in a spiral pattern, found in most spiral galaxies.

spiral density waves Gravitationally driven waves of enhanced density that move through a spiral galaxy and are responsible for maintaining its spiral arms.

spiral galaxies Galaxies that look like flat white disks with yellowish bulges at their centers. The disks are filled with cool gas and dust, interspersed with hotter ionized gas, and usually display beautiful spiral arms.

spreading centers (geological) Places where hot mantle material rises upward between plates and then spreads sideways, creating new seafloor crust.

spring (March) equinox Refers both to the point in Pisces on the celestial sphere where the ecliptic crosses the celestial equator and to the moment in time when the Sun appears at that point each year (around March 21).

spring tides The higher-than-average tides on Earth that occur at new and full moon, when the tidal forces from the Sun and Moon both act along the same line.

standard candle An object for which we have some means of knowing its true luminosity, so that we can use its apparent brightness to determine its distance with the luminosity–distance formula.

standard model (of physics) The current theoretical model that describes the fundamental particles and forces in nature.

standard time Time measured according to the internationally recognized time zones.

star A large, glowing ball of gas that generates energy through nuclear fusion in its core. The term *star* is sometimes applied to objects that are in the process of becoming true stars (e.g., protostars) and to the remains of stars that have died (e.g., neutron stars).

starburst galaxy A galaxy in which stars are forming at an unusually high rate.

star cluster *See* cluster of stars.

star–gas–star cycle The process of galactic recycling in which stars expel gas into space, where it mixes with the interstellar medium and eventually forms new stars.

star system *See* solar system.

state (quantum) *See* quantum state.

steady state theory A now-discredited theory that held that the universe had no beginning and looks about the same at all times.

Stefan–Boltzmann constant A constant that appears in the laws of thermal radiation, with value

$$\sigma = 5.7 \times 10^{-8} \frac{\text{watt}}{\text{m}^2 \times \text{Kelvin}^4}$$

stellar evolution The formation and development of stars.

stellar parallax The apparent shift in the position of a nearby star (relative to distant objects) that occurs as we view the star from different positions in Earth's orbit of the Sun each year.

stellar thermostat The regulation of a star's core temperature that comes about when a star is in both energy balance (the rate at which fusion releases energy in the star's core is balanced with the rate at which the star's surface radiates energy into space) and gravitational equilibrium.

stellar wind A stream of charged particles ejected from the surface of a star.

stratosphere An intermediate-altitude layer of Earth's atmosphere that is warmed by the absorption of ultraviolet light from the Sun.

stratovolcano A steep-sided volcano made from viscous lavas that can't flow very far before solidifying.

string theory New ideas, not yet well-tested, that attempt to explain all of physics in a much simpler way than current theories.

stromatolites Rocks thought to be fossils made by ancient microbes.

strong force One of the four fundamental forces; it is the force that holds atomic nuclei together.

subduction (of tectonic plates) The process in which one plate slides under another.

subduction zones Places where one plate slides under another.

subgiant A star that is between being a main-sequence star and being a giant; subgiants have inert helium cores and hydrogen-burning shells.

sublimation The process by which atoms or molecules escape into the gas phase from a solid.

summer (June) solstice Refers both to the point on the celestial sphere where the ecliptic is farthest north of the celestial equator and to the moment in time when the Sun appears at that point each year (around June 21).

sunspot cycle The period of about 11 years over which the number of sunspots on the Sun rises and falls.

sunspots Blotches on the surface of the Sun that appear darker than surrounding regions.

superbubble Essentially a giant interstellar bubble, formed when the shock waves of many individual bubbles merge to form a single giant shock wave.

superclusters The largest known structures in the universe, consisting of many clusters of galaxies, groups of galaxies, and individual galaxies.

supergiants The very large and very bright stars (luminosity class I) that appear at the top of an H-R diagram.

supermassive black holes Giant black holes, with masses millions to billions of times that of our Sun, thought to reside in the centers of many galaxies and to power active galactic nuclei.

supernova The explosion of a star.

Supernova 1987A A supernova witnessed on Earth in 1987; it was the nearest supernova seen in nearly 400 years and helped astronomers refine theories of supernovae.

supernova remnant A glowing, expanding cloud of debris from a supernova explosion.

surface area–to–volume ratio The ratio defined by an object's surface area divided by its volume; this ratio is larger for smaller objects (and vice versa).

synchronous rotation The rotation of an object that always shows the same face to an object that it is orbiting because its rotation period and orbital period are equal.

synchrotron radiation A type of radio emission that occurs when electrons moving at nearly the speed of light spiral around magnetic field lines.

synodic month (or **lunar month**) The time required for a complete cycle of lunar phases, which averages about $29\frac{1}{2}$ days.

synodic period (of a planet) The time between successive alignments of a planet and the Sun in our sky; measured from opposition to opposition for a planet beyond Earth's orbit, or from superior conjunction to superior conjunction for Mercury and Venus.

tangential motion The component of an object's motion directed across our line of sight.

tangential velocity The portion of any object's total velocity that is directed across (perpendicular to) our line of sight. This part of the velocity cannot be measured with the Doppler effect. It can be measured only by observing the object's gradual motion across our sky.

tectonics The disruption of a planet's surface by internal stresses.

temperature A measure of the average kinetic energy of particles in a substance.

terrestrial planets Rocky planets similar in overall composition to Earth.

theories of relativity (special and general) Einstein's theories that describe the nature of space, time, and gravity.

theory (in science) *See* scientific theory.

theory of evolution The theory, first advanced by Charles Darwin, that explains how evolution occurs through the process of natural selection.

thermal emitter An object that produces a thermal radiation spectrum; sometimes called a *blackbody.*

thermal energy The collective kinetic energy, as measured by temperature, of the many individual particles moving within a substance.

thermal escape The process in which atoms or molecules in a planet's exosphere move fast enough to escape into space.

thermal pressure The ordinary pressure in a gas arising from motions of particles that can be attributed to the object's temperature.

thermal pulses The predicted upward spikes in the rate of helium fusion, occurring every few thousand years, that occur near the end of a low-mass star's life.

thermal radiation The spectrum of radiation produced by an opaque object that depends only on the object's temperature; sometimes called *blackbody radiation.*

thermosphere A high, hot X-ray-absorbing layer of an atmosphere, just below the exosphere.

third-quarter (phase) The phase of the Moon that occurs three-quarters of the way through each cycle of phases, in which precisely half of the visible face is illuminated by sunlight.

tidal force A force that occurs when the gravity pulling on one side of an object is larger than that on the other side, causing the object to stretch.

tidal friction Friction within an object that is caused by a tidal force.

tidal heating A source of internal heating created by tidal friction. It is particularly important for satellites with eccentric orbits such as Io and Europa.

time dilation The effect in which you observe time running more slowly in reference frames moving relative to you.

timing (in astronomical research) The process of tracking how the light intensity from an astronomical object varies with time.

torque A twisting force that can cause a change in an object's angular momentum.

total apparent brightness *See* apparent brightness. The word "total" is sometimes added to make clear that we are talking about light across all wavelengths, not just visible light.

totality (eclipse) The portion of a total lunar eclipse during which the Moon is fully within

Earth's umbral shadow or a total solar eclipse during which the Sun's disk is fully blocked by the Moon.

total luminosity *See* luminosity. The word "total" is sometimes added to make clear that we are talking about light across all wavelengths, not just visible light.

total lunar eclipse A lunar eclipse in which the Moon becomes fully covered by Earth's umbral shadow.

total solar eclipse A solar eclipse during which the Sun becomes fully blocked by the disk of the Moon.

transit An event in which a planet passes in front of a star (or the Sun) as seen from Earth. Only Mercury and Venus can be seen in transit of our Sun. The search for transits of extrasolar planets is an important planet detection strategy.

transmission (of light) The process in which light passes through matter without being absorbed.

transparent Describes a material that transmits light.

tree of life (evolutionary) A diagram that shows relationships between different species as inferred from genetic comparisons.

triple-alpha reaction *See* helium fusion.

Trojan asteroids Asteroids found within two stable zones that share Jupiter's orbit but lie 60° ahead of and behind Jupiter.

tropical year The time from one spring equinox to the next, on which our calendar is based.

Tropic of Cancer The circle on Earth with latitude 23.5°N, which marks the northernmost latitude at which the Sun ever passes directly overhead (which it does at noon on the summer solstice).

Tropic of Capricorn The circle on Earth with latitude 23.5°S, which marks the southernmost latitude at which the Sun ever passes directly overhead (which it does at noon on the winter solstice).

tropics The region on Earth surrounding the equator and extending from the Tropic of Capricorn (latitude 23.5°S) to the Tropic of Cancer (latitude 23.5°N).

troposphere The lowest atmospheric layer, in which convection and weather occur.

Tully–Fisher relation A relationship among spiral galaxies showing that the faster a spiral galaxy's rotation speed, the more luminous it is. It is important because it allows us to determine the distance to a spiral galaxy once we measure its rotation rate and apply the luminosity–distance formula.

turbulence Rapid and random motion.

21-cm line A spectral line from atomic hydrogen with wavelength 21 cm (in the radio portion of the spectrum).

ultraviolet light Light with wavelengths that fall in the portion of the electromagnetic spectrum between visible light and X rays.

umbra The dark central region of a shadow.

unbound orbits Orbits on which an object comes in toward a large body only once, never to return; unbound orbits may be parabolic or hyperbolic in shape.

uncertainty principle The law of quantum mechanics that states that we can never know both a particle's position and its momentum, or both its energy and the time it has the energy, with absolute precision.

universal law of gravitation The law expressing the force of gravity (F_g) between two objects, given by the formula

$$F_g = G\frac{M_1 M_2}{d^2}$$

$$\left(\text{where } G = 6.67 \times 10^{-11}\,\frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)$$

universal time (UT) Standard time in Greenwich (or anywhere on the prime meridian).

universe The sum total of all matter and energy.

up quark One of the two quark types (the other is the down quark) found in ordinary protons and neutrons; has a charge of $+\frac{2}{3}$.

velocity The combination of speed and direction of motion; it can be stated as a speed in a particular direction, such as 100 km/hr due north.

virtual particles Particles that "pop" in and out of existence so rapidly that, according to the uncertainty principle, they cannot be directly detected.

viscosity The thickness of a liquid described in terms of how rapidly it flows; low-viscosity liquids flow quickly (e.g., water), while high-viscosity liquids flow slowly (e.g., molasses).

visible light The light our eyes can see, ranging in wavelength from about 400 to 700 nm.

visual binary A binary star system in which both stars can be resolved through a telescope.

voids Huge volumes of space between superclusters that appear to contain very little matter.

volatiles Substances, such as water, carbon dioxide, and methane, that are usually found as gases, liquids, or surface ices on the terrestrial worlds.

volcanic plains Vast, relatively smooth areas created by the eruption of very runny lava.

volcanism The eruption of molten rock, or lava, from a planet's interior onto its surface.

waning (phases) The set of phases in which less and less of the visible face of the Moon is illuminated; the phases that come after full moon but before new moon.

watt The standard unit of power in science; defined as 1 watt = 1 joule/s.

wavelength The distance between adjacent peaks (or troughs) of a wave.

waxing (phases) The set of phases in which more and more of the visible face of the Moon is becoming illuminated; the phases that come after new moon but before full moon.

weak bosons The exchange particles for the weak force.

weak force One of the four fundamental forces; it is the force that mediates nuclear reactions, and it is the only force besides gravity felt by weakly interacting particles.

weakly interacting particles Particles, such as neutrinos and WIMPs, that respond only to the weak force and gravity; that is, they do not feel the strong force or the electromagnetic force.

weather The ever-varying combination of winds, clouds, temperature, and pressure in a planet's troposphere.

weight The net force that an object applies to its surroundings; in the case of a stationary body on the surface of Earth, it equals mass × acceleration of gravity.

weightlessness A weight of zero, as occurs during free-fall.

white dwarf limit (or **Chandrasekhar limit**) The maximum possible mass for a white dwarf, which is about $1.4M_{\text{Sun}}$.

white dwarfs The hot, compact corpses of low-mass stars, typically with a mass similar to that of the Sun compressed to a volume the size of Earth.

white dwarf supernova A supernova that occurs when an accreting white dwarf reaches the white-dwarf limit, ignites runaway carbon fusion, and explodes like a bomb; often called a *Type Ia supernova.*

WIMPs A possible form of dark matter consisting of subatomic particles that are dark because they do not respond to the electromagnetic force; stands for *weakly interacting massive particles.*

winter (December) solstice Refers both to the point on the celestial sphere where the ecliptic is farthest south of the celestial equator and to the moment in time when the Sun appears at that point each year (around December 21).

worldline A line that represents an object on a spacetime diagram.

wormholes The name given to hypothetical tunnels through hyperspace that might connect two distant places in our universe.

X-ray binary A binary star system that emits substantial amounts of X rays, thought to be from an accretion disk around a neutron star or black hole.

X-ray burster An object that emits a burst of X rays every few hours to every few days; each burst lasts a few seconds and is thought to be caused by helium fusion on the surface of an accreting neutron star in a binary system.

X-ray bursts Bursts of X rays coming from sudden ignition of fusion on the surface of an accreting neutron star in an X-ray binary system.

X rays Light with wavelengths that fall in the portion of the electromagnetic spectrum between ultraviolet light and gamma rays.

Zeeman effect The splitting of spectral lines by a magnetic field.

zenith The point directly overhead, which has an altitude of 90°.

zodiac The constellations on the celestial sphere through which the ecliptic passes.

zones (on a jovian planet) Bright bands of rising air that encircle a jovian planet at a particular set of latitudes.

Credits

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You Are Here in Space

One of the best reasons to study modern astronomy is to learn abou
universe. This visual will lead you through the basic levels of structur
universe as a whole and ending with Earth.

The Observable Universe

The background illustration depicts the overall distribution of galaxies in our observable universe; individual galaxies are microscopic on this scale. The portion of the universe that we can, in principle, observe is limited by the age of the universe: Because our universe is about 14 billion years old, we can see no more than about 14 billion light-years in any direction. Measurements indicate that the observable universe contains more than 100 billion galaxies.

The Local Group

This image shows the largest galaxies in our Local Group. Most galaxies are memb
to a few dozen galaxies, such as our own Local Group, or larger clusters containing up t

Putting Space in Perspective

One good way to put the vast sizes and distances of astronomical objects into perspective is with a scale model. In this book, we'll build perspective using a model that shows our solar system at *one-ten-billionth* its actual size.

On the 1-to-10 billion scale, Earth is only about the size of a ballpoint in a pen (1 millimeter across).

On the 1-to-10 billion scale, the distance from the Sun to the Earth is about 15 meters.

On the 1-to-10 billion scale, the Sun is about the size of a large grapefruit (14 centimeters across).

t your place in the
e, starting with the

ers of small groups of up
o a few thousand galaxies.

m factor ≈ 40

nic Cloud

The Milky Way Galaxy

This illustration shows what the Milky Way Galaxy would look like from the outside. Our galaxy is one of the three largest members of the Local Group. The Milky Way contains more than 100 billion stars — so many stars that it would take thousands of years just to count them out loud.

The Nearest Sta

**This image shows the lo
so their sizes have been**
Milky Way brings us to the
we now know that many (

61 Cygni

Ross 154

Our Sun is a star, just like the many stars we see in the night sky.

The Voyage scale model solar system uses this 1-to-10 billion scale, making it possible to walk to the outermost planets in just a few minutes.

This map shows planet locations in the Voyage model (Washington, DC). Keep in mind that planets actually follow orbits that go all the way around the Sun.

ars

locations of nearby stars; stars would be atom-sized on this scale, n greatly exaggerated for visibility. Zooming in on a tiny piece of the e nearby stars of our *local solar neighborhood.* While we *see* only stars, (perhaps most) stars are orbited by planets.

The Solar System

This diagram shows the orbits of the planets around the Sun; the planets themselves are microscopic on this scale. Our solar system consists of the Sun and all the objects that orbit it, including the planets and their moons, and countless smaller objects such as asteroids and comets.

On the 1-to-10 billion scale, you'd have to cross the United States to reach the nearest stars.

One light-year becomes 1000 kilometers on the Voyage scale, so even the nearest stars are more than 4000 kilometers away, equivalent to the distance across the United States.

The Earth–Moon System

This diagram shows Earth, the Moon, and the Moon's orbit to scale. We must magnify the image of our solar system another 10,000 times to get a clear view of our home planet and its constant companion, our Moon.

Earth

You are here. The physical sizes of human beings and even the planet on which we live are almost unimaginably small compared to the vastness of space. Yet in spite of this fact, we have managed to measure the size of the observable universe and to discover how our lives are related to the stars.

A water molecule is a million times smaller than a grain of sand. On the 1-to-10 billion scale, *you* would be slightly smaller than a water molecule.

These comparisons show how tiny we are compared to the solar system in which we live, but we've only just begun to cover the range of scales in the universe.

- To appreciate the size of our galaxy, consider that the stars on this scale are like grapefruits thousands of kilometers apart, yet there are so many that it would take you thousands of years to count them one-by-one.
- And with more than 100 billion galaxies, the observable universe contains a total number of stars comparable to the number of grains of dry sand on *all the beaches on Earth* combined.

This photo of the Hubble Ultra Deep Field shows galaxies visible in a patch of sky that you could cover with a grain of sand held at arm's length.

You Are Here in Time

How does your life fit into the scale of time? We can gain perspective on this question with a *cosmic calendar* on which the 14-billion-year history of the universe is scaled down using a single calendar year. The Big Bang occurs at the stroke of midnight on January 1, and the present is the last second of December 31.

The Early Universe

Observations indicate that the universe began about 14 billion years ago in what we call the *Big Bang*. All matter and energy in the universe came into being at that time. The expansion of the universe also began at that time, and continues to this day.

Galaxy Formation

Galaxies like our Milky Way gradually grew over the next few billion years. Small collections of stars and gas formed first, and these smaller objects merged to form larger galaxies.

This image shows the cosmic microwave background, *which comes to us from all directions in space and represents radiation leftover from the Big Bang—January 1 on the cosmic calendar.*

Globular clusters containing up to a million stars were among the first objects to form in the universe. This cluster (M80) formed more than 12 billion years ago, about February 1 on the cosmic calendar.

These cubes represent the first billion years of expansion for a small portion of the universe. During this time, gravity began to clump matter into stars and galaxies. The universe is still expanding today and continues to form new stars.

Many young galaxies grew by colliding and merging with other galaxies. This image shows a collision that occurred about 11.4 billion years ago, around March 2 on the cosmic calendar, but the collision is so far away that the light from it is just reaching us now.

Element Production by Stars

The early universe contained just three chemical elements: hydrogen, helium, and a tiny amount of lithium. Essentially all of the other elements were manufactured by nuclear fusion in stars, or by the explosions that end stellar lives. The elements that now make up Earth — and life — were created by stars that lived before our solar system was born.

	MAY	JUNE	JULY	AUGUST

Stars are born in clouds of gas and dust; planets may form in surrounding disks.

Massive stars explode when they die, scattering the elements they've produced into space.

Stars shine with energy released by nuclear fusion, which ultimately manufactures all elements heavier than hydrogen and helium.

Each new generation of stars is born from gas that has been recycled and enriched with new elements from prior generations of stars. This cycle started with the first generation of stars and continues to this day.

This illustration shows what t
Sun and planets finished form

Birth of Our Solar System

Our solar system was born from the gravitational collapse of an interstellar cloud of gas about $4\frac{1}{2}$ billion years ago, or about September 3 on the cosmic calendar. The Sun formed at the center of the cloud while the planets, including Earth, formed in a disk surrounding it.

Life on Earth

We do not know exactly when life arose on Earth, but fossil evidence indicates that it was within a few hundred million years after Earth's formation. Nearly three billion more years passed before complex plant and animal life evolved.

SEPTEMBER | OCTOBER | NOVEMBER | DECEMBER

SEP 3

SEP 22

DEC 17

DEC 26

This rock formation in Greenland holds the oldest known evidence of life on Earth, dating to more than 3.85 billion years ago, or September 22 on the cosmic calendar.

Fossil evidence shows a remarkable increase in animal diversity beginning about 540 million years ago — December 17 on the cosmic calendar. We call this the Cambrian explosion.

Dinosaurs arose about 225 million years ago — December 26 on the cosmic calendar. Mammals arose around the same time.

he solar system may have looked like shortly before the ing.

Dinosaurs went extinct, probably due to an asteroid or comet impact, about 65 million years ago, which was only yesterday (December 30) on the cosmic calendar.

Human History

On the cosmic calendar, our hominid ancestors arose only a few hours ago, and all of recorded human history has occurred in just the last 15 seconds before midnight.

You

The average human life span is only about two-tenths of a second on the cosmic calendar.

Our early ancestors had smaller brains, but probably were walking upright by about 5 million years ago—December 31, 9 PM on the cosmic calendar.

Modern humans arose about 40,000 years ago, which is only about two minutes ago (December 31, 11:58 PM) on the cosmic calendar.

On the cosmic calendar, our ancestors began to master agriculture only 25 seconds ago ...

...the Egyptians built the pyramids only 11 seconds ago ...

...we learned that Earth is a planet orbiting the Sun only 1 second ago ...

11:59:59.95 PM

...and a typical college student was born only 0.05 second ago.

Your Road to Success in Astronomy

Bennett/Donahue/Schneider/Voit's ***The Essential Cosmic Perspective* with MasteringAstronomy,® Sixth Edition,** provides a solid foundation for success in astronomy with features that make it a best-selling text, including:

- A clear and consistent learning path
- Highly-informative, easy-to-interpret visuals
- MasteringAstronomy, the most advanced and widely-used homework and tutorial system available
- Coverage of the process of science integrated throughout the text

To learn more, please turn the page.

Identify • what's important in the text and visuals

Learning goals identify key ideas in each chapter

The Essential Cosmic Perspective's **clear and directed learning path** makes it easy to determine which concepts are most important. Each chapter is organized around consistent learning goals to focus student attention and to ensure that only material relevant to the key concepts is covered.

Motivational Learning Goals phrased as engaging questions begin each chapter, identifying the most important concepts ahead.

One section, one learning goal—each section is written to address a single learning goal, providing a focused path through key concepts.

Visual summaries at the end of each chapter use words and figures to provide a recap of answers to the learning goal questions, reinforcing the key concepts from the chapter.

Inspire learning with outstanding visuals

Carefully designed visuals illustrate important concepts and processes in a systematic, intentional way that helps readers interpret visual information.

NEW! Scale of Space and Time foldout diagrams provide a comprehensive, visual overview of scale to help reinforce one of the most important concepts in astronomy.

Annotated figures and photos contain blue text that points out the most important information presented in complex figures, photos, and graphs to help build visual interpretation skills.

Cosmic Context Figures combine text and illustrations into accessible and coherent visual summaries of key topics and processes.

Media • helps students and instructors succeed

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Math Skills Tutorials review the basic math topics needed for astronomy courses that cover quantitative material. Each tutorial includes a few brief videos that go over important skills and provide problem-solving examples, followed by assessment.

***New York Times* Reading Quizzes** ask students to read a *New York Times* science article and answer a set of multiple-choice questions about it. The quizzes are designed not only to help integrate current events into homework assignments, but also to help students build basic critical thinking skills such as reading comprehension, analysis of arguments, and applying knowledge to new scenarios.

Additional tutorials incorporate interactive questions and visuals to help solidify understanding of key topics such as tides, the electromagnetic spectrum, and cosmic distances.

Engage • with astronomy in and out of the classroom

Encourage learning inside the classroom

The Essential Cosmic Perspective provides a number of **in-class tools** to help foster **active learning and engagement.**

Group Work Exercise

43. *Refuting the Nebular Theory?* In this exercise, you'll consider the following three hypothetical discoveries concerning systems of planets around other stars:
    a. a system with a lone planet that is small and dense like a terrestrial planet but has a Jupiter-like orbit
    b. a system in which three terrestrial planets orbit their star beyond the orbital distance of two jovian planets
    c. a majority of planetary systems have jovian planets closer than 1 AU to their star and terrestrial planets located beyond 5 AU

    Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Advocate* (argues in favor of the nebular theory), *Skeptic* (points out weaknesses in the nebular theory), and *Moderator* (leads group discussion and makes sure everyone contributes). For each discovery, discuss whether it (1) could be explained with the nebular theory, (2) could be explained with a revision of the nebular theory, or (3) would force us to abandon the nebular theory. After listening to the *Advocate* and *Skeptic* discuss each discovery, the *Scribe* and *Moderator* should choose option (1), (2), or (3) and write down your team's reasoning.

NEW! Each chapter includes a Group Work Exercise that can be done easily in class to encourage peer learning and in-class participation, one of the most effective ways to learn and retain concepts.

MasteringASTRONOMY

Reading Quiz for Ch. 3: The Science of Astronomy

Which of the following is not a contribution made by Tycho Brahe to the Copernican Revolution?

A. He measured the parallax of a supernova and showed that it was further away than the Moon.
B. He measured the parallax of a comet and showed that it was further away than the Moon.
C. He measured the parallax of stars, showing that the Earth orbits the Sun.
D. He measured the positions of the planets with unprecedented accuracy, making it possible for Kepler to determine their orbits.

NEW! Reading Quiz Clicker Questions are multiple-choice questions based on the Learning Goals from the book to make sure reading assignments are done before lecture and to help identify the concepts that need more in-depth coverage during class.

MasteringASTRONOMY

Interactive Figures and Photos, which are animated versions of key figures from the book, can be used during class to illustrate key concepts and bring static visuals to life.

Encourage learning outside the classroom

Students have **abundant resources** at their fingertips to help extend their astronomy learning experience outside of class.

MasteringASTRONOMY

Coordinator: _____

Reporter: _____

Skeptic: _____

Chapter 5 Group Activity: Observing with Telescopes

Overview: When astronomers are making observations, the location of their telescopes depends on what kind of light they are trying to observe. Certain wavelengths of light cannot penetrate Earth's atmosphere, and some wavelengths can only penetrate partially. This is the reason why we send telescopes into space, although they are much more expensive and difficult to maintain.

Procedure:

Part A: The following figure illustrates the approximate depth to which different wavelengths of light penetrate Earth's atmosphere.

1. Which wavelengths are **not** able to reach sea level?

2. Which wavelengths **are** able to reach sea level?

3. Which wavelengths penetrate Earth's atmosphere only to high mountaintops?

Group Work Activities can be assigned and completed outside the classroom, encouraging peer learning.

NEW! WorldWide Telescope tours available within MasteringAstronomy® give students the opportunity to interactively explore a variety of celestial objects using real telescope imagery.

Visual Skills Check activities following each chapter summary give students the opportunity to practice their visual interpretation skills with a brief set of multiple choice questions based on a figure, graph, or photo.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 2 Visual Quiz at www.masteringastronomy.com.

The figure above is a typical diagram used to describe Earth's seasons. Use this figure to answer questions 1–5.

1. Which of the four labeled points (A through D) represents the beginning of summer for the Northern Hemisphere?
2. Which of the four labeled points represents the beginning of summer for the Southern Hemisphere?
3. Which of the four labeled points represents the beginning of spring for the Northern Hemisphere?
4. Which of the four labeled points represents the beginning of spring for the Southern Hemisphere?
5. Diagrams like the one shown in the figure are useful for representing seasons, but they can also be misleading because they exaggerate the sizes of Earth and the Sun relative to the orbit. If Earth were correctly scaled relative to the orbit in the figure, how big would it be?
   a. about half the size shown
   b. about 2 millimeters across
   c. about 0.1 millimeter across
   d. microscopic

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