PART 1

OUR ISLAND IN SPACE

When you gaze out toward the horizon from a mountaintop, the Earth seems endless, and before the modern era, many people thought it was. But to astronauts flying to the Moon, the Earth looks like a small, shining globe—they can see half the planet in a single glance. From the astronauts' perspective, we are living on an island in space.

Earth may not be endless, but it is a very special planet: its temperature and composition, unlike those of the other planets in the Solar System, make it habitable. In Part I of this book, we first learn in Chapter 1 scientific ideas about how the Earth, and the Universe around it, came to be. Then, in Chapter 2, we take a quick tour of the planet to get a sense of its composition and its various layers. With this background, we're ready to move on to Chapter 3, where we'll encounter the twentieth-century revolution in geology that yielded the set of ideas we now call the theory of plate tectonics. In Chapter 4, we'll delve into the physics behind this theory (which proposes that the outer layer of the Earth consists of plates that move with respect to each other) and its principles. We'll see that plate tectonics provides a rational explanation for a great variety of geologic features—from the formation of continents to the distribution of fossils—and is truly the unifying concept for all of geology.

1 **Cosmology and the Birth of Earth**
2 **Journey to the Center of the Earth**
3 **Drifting Continents and Spreading Seas**
4 **The Way the Earth Works: Plate Tectonics**

An astronaut taking a space walk outside of the International Space Station could not survive without a space suit. The hospitable Earth System—land, air, and water—lies 380 km (235 mi) below.

This Hubble Space Telescope image shows the Orion Nebula, a cloud of gas and dust 24 light years across, in which new stars are forming.

CHAPTER 1

Cosmology and the Birth of Earth

I believe everyone should have a broad picture of how the Universe operates and our place in it. It is a basic human desire. And it also puts our worries in perspective.

—*Stephen Hawking (British cosmologist, born 1942)*

LEARNING OBJECTIVES

By the end of this chapter, you should understand . . .

- how people's perceptions of Earth's place in the Universe have changed over the centuries.
- modern concepts concerning the basic architecture of our Universe and its components.
- the evidence for the expanding Universe and the Big Bang theory.
- where the elements comprising matter came from.
- the nebula theory, a scientific model that explains how stars and planets form.

1.1 Introduction

Sometime in the distant past, humans developed the capacity for complex, conscious thought. This amazing ability, which distinguishes our species from all others, brought with it the gift of curiosity, an innate desire to understand and explain the workings and origin of the **Universe**, meaning space and everything it contains, including our home, the Earth. For most of human history, such musings have spawned legends in which heroes, gods, and goddesses used supernatural powers to ignite the Sun, to make the Moon glow, to mold the Earth from nothingness and sculpt its surface into dramatic shapes, and to speckle the night with points of light. Only recently have people applied scientific principles (see Box P.1) to the systematic study of the overall structure and history of the Universe, thereby establishing the modern discipline of scientific **cosmology**. In the context of scientific cosmology, the Universe contains of two basic entities—**matter**, the substance that makes up objects, and **energy**, the inherent ability of a region of space and the matter within it to do "work" (to change itself and/or its surroundings). We can refer to the amount of matter in an object as its **mass**, so an object with greater mass contains more matter.

Scientific cosmology provides a foundation from which we can begin to explore the composition, structure, and evolution of the Earth. So we begin this book on geology, the study of the Earth, with a chapter that outlines key principles of scientific cosmology. In effect, we must look outward in order to be able understand what we'll see when we look inward at the Earth (Fig. 1.1). We start by characterizing the architecture of the Universe overall and of our Solar System in particular. Then we introduce the Big Bang theory, which researchers use to explain the formation of the Universe, and the production of the elements that eventually came together to form the Sun, Earth, and other **celestial objects** (naturally occurring bodies in the Universe). We conclude by discussing the nebular theory for the birth of the Earth itself.

1.2 An Image of Our Universe

What Is the Structure of the Universe?

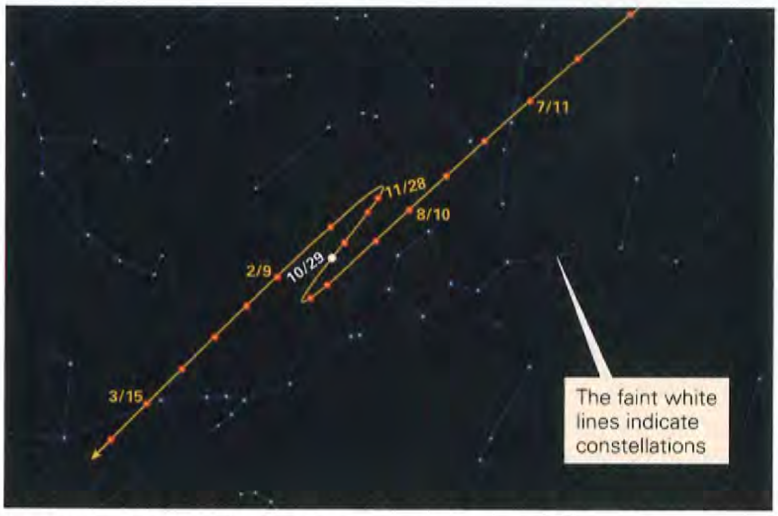
Think about the mysterious spectacle of a clear night sky (Fig. 1.2a). What objects are up there? How big are they? How far away are they? How do they move? How are they arranged? Ancient cultures around the world thought long and hard about such questions, and by 3,000 years ago, keen observers—the

FIGURE 1.1 This iconic image of "Earthrise," taken by astronauts orbiting the Moon, profoundly influenced humanity's perception of our home planet. Since we live on an island in space, we need to understand space in order to understand the Earth.

FIGURE 1.2 The sky at night, showing a variety of celestial objects.

(a) Imagine what it would be like *not* to know what celestial objects, such as the Moon, are. Until the past few hundred years, we didn't.

(b) When viewed for the whole night, stars in the northern hemisphere appear to revolve around the North Star.



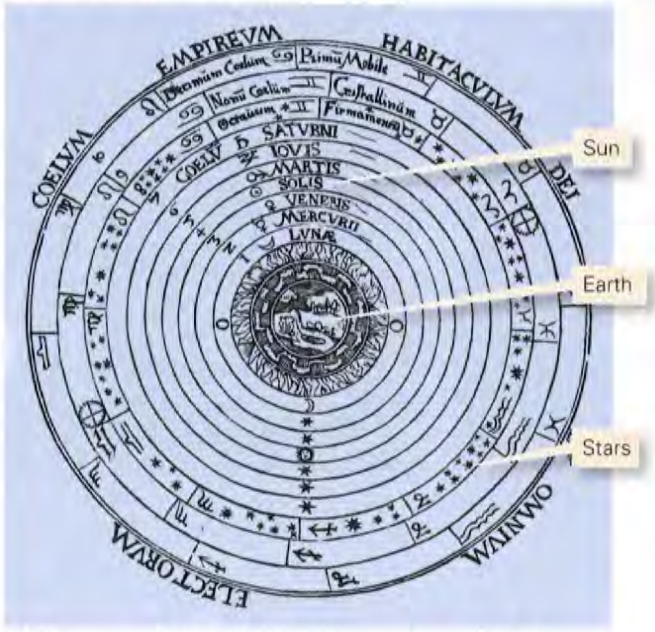
(c) If you track certain objects in the night sky, they appear to move relative to the backdrop of stars. These "wanderers" are the planets. The numbers are dates (month/day), indicating when the planet shown was at a given location.

first **astronomers** (people who study celestial bodies)—had realized that what they could see above had a recognizable order. Specifically, most of the thousands of points of light visible to the naked eye move slowly across the sky nightly, as if revolving around a fixed point (Fig. 1.2b), and the positions of these points relative to each other remains fixed. These points became known as the *stars*. In contrast, a handful of the lights in the night sky etch seemingly complex paths across the night sky, moving relative to one another and relative to the backdrop of stars (Fig. 1.2c). These lights came to be known as the *planets* (from the Greek *planēs*, which means "wanderer").

Early observers did not know what the stars and planets were, and they didn't understand their own relationship with the Earth, Moon, and Sun. It wasn't at all obvious, in fact, that the Earth is a planet and the Sun is a star. In the days of the Greek philosopher Homer (ca. 850 B.C.E.), for example, people in the Mediterranean region held the belief that the Earth was a flat disk, with land toward the center and water around the margins, and that this disk lay at the center of a celestial sphere, a dome to which the stars were attached. Philosophers of Homer's day argued about the nature of the Sun and why it produced heat and light: to some, the Sun was a burning bowl of oil, while to others it was a ball of red-hot iron. Many favored the notion that movements of celestial bodies represented the activities of gods and goddesses, and they named *constellations*—distinctive arrangements of stars—after gods and goddesses. Other societies developed quite different mythologies, full of symbolism, in which to interpret the heavens.

In the Western world, two distinct schools of thought developed concerning the arrangement of stars and planets and their relationship to the Earth, Sun, and Moon. The first school advocated a **geocentric model** (Fig. 1.3a), in which the Earth sits without moving at the center of the Universe while the Moon and the planets whirl around it in circular orbits, all within a shell of stars. The second school advocated a **heliocentric model** (Fig. 1.3b), in which the Sun lies at the center of the Universe, with the Earth and other planets orbiting around it. The geocentric image gained a widespread following due to the influence of an Egyptian mathematician, Ptolemy (100–170 C.E.), who developed equations that seemed to predict the wanderings of the planets, in the context of the geocentric model, with remarkable accuracy. During the Middle Ages (ca. 476–1400 C.E.), church leaders in Europe adopted Ptolemy's geocentric image as dogma because it seemed to jus-

FIGURE 1.3 Contrasting views of the Universe, as drawn by artists hundreds of years ago.



(a) The geocentric image of the Universe shows the Earth at the center, surrounded by air, fire, and the other planets, all contained within the globe of the stars.

(b) The heliocentric image of the Universe shows the Sun at the center, as envisioned by Copernicus.

tify the comforting thought that humanity's home occupies the most important place in the Universe. Eventually, anyone who disagreed with this view risked charges of heresy.

Then came the Renaissance. In 15th-century Europe, bold thinkers spawned a new age of exploration and scientific discovery. Thanks to the efforts of Nicolaus Copernicus (1473–1543) and Galileo Galilei (1564–1642), people eventually came to realize that the Earth and planets did indeed orbit the Sun, so the Earth could not possibly be at the center of the Universe. The idea solidified when Johannes Kepler (1571–1630) showed that Ptolemy was wrong and that planets follow elliptical orbits. And when Isaac Newton (1643–1727) explained **gravity**, the attractive force that one mass exerts on another (**Box 1.1**), it finally became possible to understand why celestial objects display the motions that they do.

Stars and Galaxies

After Galileo popularized the telescope, astronomers gained the ability to see and measure features progressively farther into space and gradually refined our understanding of the Universe's structure. We now realize that, although it looks like a point of light, a **star** is actually an immense sphere of incandescent gas that emits intense energy—stars are just like our Sun but lie farther away. Furthermore, stars are not scattered randomly through the Universe; rather, gravity holds them together in immense groups called **galaxies**. Our Sun joins with over 300 billion other stars to form the *Milky Way galaxy*. From our vantage point on Earth, the Milky Way looks like a hazy band (**Fig. 1.4a**), but if we could view the Milky Way from a great distance, it would look like a flattened spiral with great curving arms slowly swirling around a glowing, disk-like center (**Fig. 1.4b**). Presently, our Sun lies near the outer edge of one of these arms. Astronomers estimate that more than 100 billion galaxies constitute the visible Universe (**Fig. 1.4c**).

Clearly, human understanding of Earth's place in the Universe evolved radically over the past few centuries. Neither the Earth nor the Sun, nor even the Milky Way, occupies the center of the Universe. While the Earth is quite special to us because we live here, there's nothing particularly special about its position in the Universe.

The Nature of Our Solar System

Our Sun's gravitational pull holds on to many objects which, together with the Sun, comprise the **Solar System** (**Fig. 1.5a**). Most of the mass of the Solar System—99.8%, to be exact—resides in the Sun itself. The remaining 0.2% includes a great variety of objects, the largest of which are planets. Astronomers define a **planet** as an object that orbits a star, is roughly spherical, and has "cleared its neighborhood of other objects." The last phrase in this definition sounds a bit strange at first, but it merely implies that a planet's gravity has pulled in all particles of matter in its orbit. According to this definition, formalized in 2005, our Solar System includes eight planets—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Until 2005, astronomers considered one more object, Pluto, to be a planet. But Pluto has not cleared its orbit, so it does not fit the modern definition of a planet and has been dropped from the roster. The

BOX 1.1 SCIENCE TOOLBOX . . .

Force and Energy

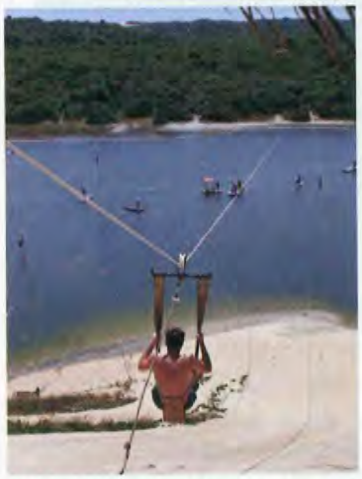
Isaac Newton defined a *force* as simply a push or pull that causes the velocity of an object to change in magnitude (speed) and/or direction. In your everyday experience, you constantly see and/or feel the effect of forces. Forces can speed objects up or slow them down. Forces can also tear, stretch, squash, spin, and twist objects and can make them float or sink. Any system (a defined volume of space and everything in it) contains *energy*, meaning that it has an inherent ability or capacity to do work. In this context, *work* refers to the product of the force and the distance over which the force is acting—you do work when you lift this book 10 cm, and you do more work when you lift it 20 cm. When work is done, energy transfers from one part of a system to another, but the total amount of energy in the system cannot be created or destroyed.

Physicists (scientists who study matter, energy, and the interactions between them) distinguish between two general types of force. The first type, a *contact force*, or *mechanical force*, results when one *mass* moves and comes in contact with another. You apply a mechanical force to a boulder when you push on it (**Fig. Bx1.1a**), and the wind applies a mechanical force to a sail when it blows. The second type, a non-contact force, or *field force*, applies across a distance; gravity and magnetism serve as examples. *Gravity* is the force of attraction between two masses—it is what holds you to the surface of the Earth and pulls objects from higher elevations to lower ones (**Fig. Bx1.1b**). The strength of gravity depends on the quantity of matter in the two masses and on the distance between them. For example, you feel a much stronger gravitational pull to the huge Earth than you do to a small baseball. Weight is the force that an object exerts due to gravitational pull, so the stronger the gravitational pull, the greater the weight of an object. For example, on the Moon, you weigh much less than on the Earth because the Moon is smaller so it exerts less gravitational pull. **Magnetism**, simplistically, is the force generated by electricity flowing in a wire, or by special materials called magnets. Unlike gravity, magnetic force can be attractive (pulling objects together) or repulsive (pushing them apart). Over short distances, the magnetic force of even a small magnet can be larger than the gravitational force produced by the Earth; thus, you can overcome gravity and lift objects with a magnet (**Fig. Bx1.1c**).

Physicists also distinguish between two general types of energy. *Kinetic energy* is the energy that an object has when it's moving. For example, a boulder bounding down a hill has kinetic energy. *Potential energy*, in contrast, is the energy held in an object being acted on by a field force. A boulder sitting at the top of a hill stores potential energy because it is being pulled on by the Earth's gravity but isn't moving. Energy in one form can be transformed into energy in another. When the boulder starts rolling, its potential energy transforms into kinetic energy. Similarly, light energy (a form of electromagnetic energy) can be absorbed by a solar panel, which changes it into electricity that can cause a car to move.

FIGURE Bx1.1 Examples of the forces of nature in everyday life. Mechanical and field forces are very familiar.

(a) Pushing a boulder is a mechanical force.



(b) Gravity, a field force, pulls a person down a zip line.

(c) A magnet produces a field force sufficient to hold onto these clips.

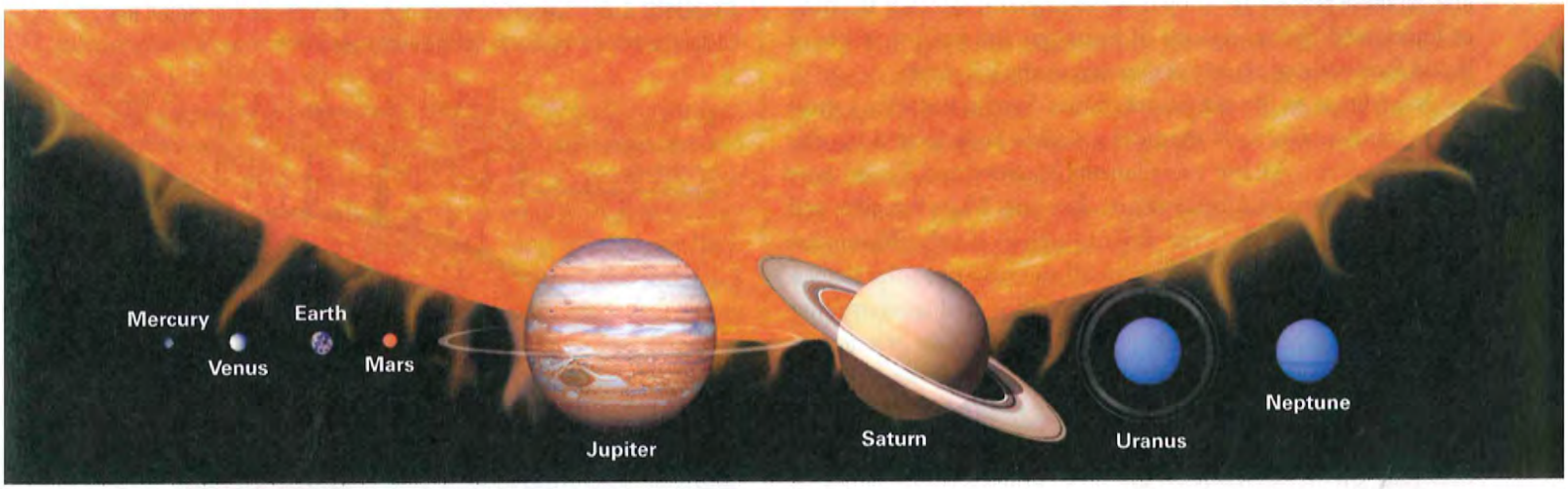
FIGURE 1.4 A galaxy may contain about 300 billion stars.

(a) The Milky Way on a clear night. The "haze" actually consists of millions of faraway stars.

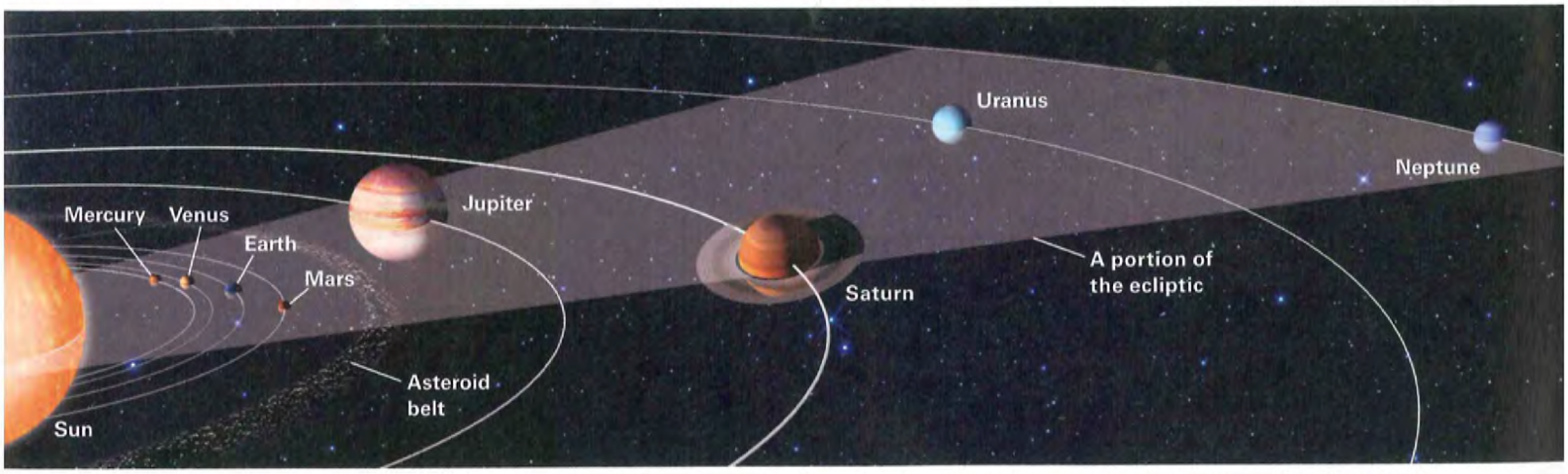
(b) A spiral galaxy that looks like the Milky Way, as viewed from the top.

(c) A Hubble Space Telescope view of deep space showing some of the billions of galaxies in the Universe.

FIGURE 1.5 The relative sizes and positions of planets in the Solar System.



(a) Relative sizes of the planets. All are much smaller than the Sun, but the gas-giant planets are much larger than the terrestrial planets. Jupiter's diameter is about 11.2 times greater than that of Earth.



(b) Relative positions of the planets. This figure is not to scale. If the Sun in this figure was the size of a large orange, the Earth would be the size of a sesame seed 15 meters (49 feet) away. Note that all planetary orbits lie roughly in the same plane, called the ecliptic.

eight planets orbit the Sun in the same direction and more or less in the same plane, called the **ecliptic** (Fig. 1.5b).

Our Solar System is not alone in hosting planets. Land-based instruments, as well as those of the Kepler Space Telescope (launched into orbit in 2009), have allowed astronomers to locate about 2,000 *exoplanets* (planets that orbit stars other than our Sun) as of 2015. Some of these are similar in size to the Earth. In fact, astronomers now estimate that the Milky Way hosts about 14 billion Earth-sized planets.

Planets in our Solar System differ radically from one another both in size and composition. The inner planets (Mercury, Venus, Earth, and Mars), the ones closer to the Sun, are relatively small. These are the **terrestrial planets** because, like Earth, they consist of a shell of rock surrounding a ball of metal. The outer planets (Jupiter, Saturn, Uranus, and Neptune) are known as the **giant planets**, or Jovian planets. These planets are indeed huge—Jupiter, for example, contains 318 times as much mass as the Earth, and accounts for about 71% of the non-solar mass in the Solar System. The overall composition of giant planets differs markedly from that of terrestrial planets. Specifically, most of the mass of Neptune and Uranus consists of solid water, ammonia, and methane, so these planets are known as the *ice giants*. Most of the mass of Jupiter and Saturn consists of hydrogen and helium, in gas or liquid form—these planets are known as the *gas giants*.

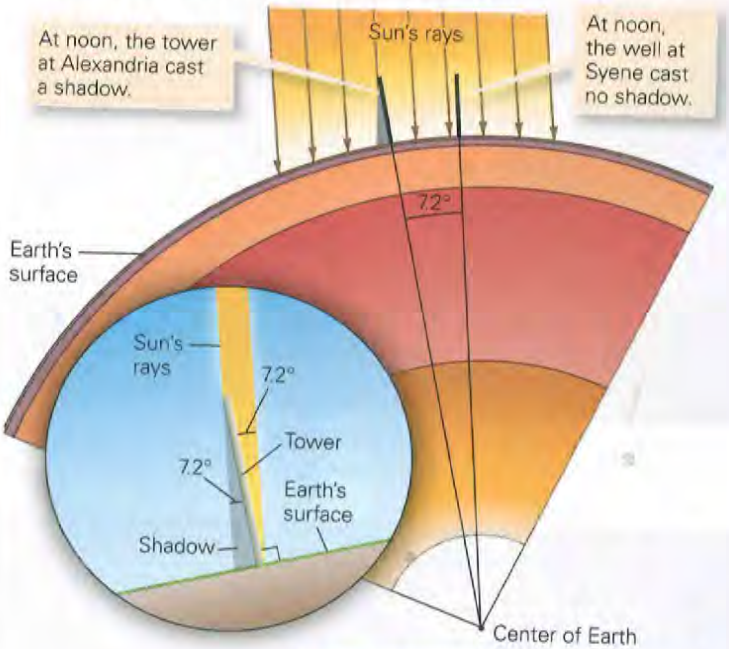
In addition to the planets, the Solar System contains a great many smaller objects. A **moon** is a sizable body locked in orbit around a planet. All but two planets (Mercury and Venus) have moons in varying numbers—Earth has one, Mars has two, and Jupiter has at least 63. Some moons, such as Earth's Moon, are large and spherical, but many are small and have irregular shapes. **Asteroids** are rocky and/or metallic objects, with diameters ranging from less than 1 cm to about 930 km. Millions of asteroids occupy a belt between the orbits of Mars and Jupiter. About a trillion bodies of ice lie outside the orbit of Neptune. (We're using the word *ice* to mean not only frozen water but also other solid materials that could exist in gas form under conditions found at the Earth's surface; examples include carbon dioxide, methane, and ammonia.) Most of these icy bodies are tiny, but a few (including Pluto) are spheres with diameters of over 2,000 km and are known as *dwarf planets*. The largest dwarf planet, Eris, found in 2003, is about 20% larger than Pluto. The gravitational pull of planets has sent some of the icy objects on paths that take them into the inner part of the Solar System, where they release long tails of gas—these objects are **comets** (see Chapter 2).

Developing a Sense of Shape and Scale

The concept that "space is vast" has become ingrained in modern culture—indeed, we use the term *astronomical distance* to mean really, really far away. How did our sense of the scale of the Universe, and the objects in it, come to be?

Let's start by considering the dimensions of the Earth itself. The Greek astronomer Eratosthenes (ca. 276–194 B.C.E.), came up with the first good estimate. Eratosthenes served as chief of the library in Alexandria, Egypt, one of the great ancient centers of learning in the ancient Mediterranean region. One day, he came across a report noting that in the southern Egyptian city of Syene (modern-day Aswan), the Sun lit the base of a deep vertical well precisely at noon on the first day of summer. Eratosthenes deduced that the Sun's rays at noon on this day must be exactly perpendicular to the Earth's surface at Syene, and that if the Earth was spherical, then the Sun's rays could not simultaneously be perpendicular to the Earth's surface at Alexandria, 800 km to the north. So on the first day of summer, Eratosthenes measured the shadow cast by a tower in Alexandria at noon. The angle between the tower and the Sun's rays, as indicated by the shadow's length, proved to be 7.2° (Fig. 1.6). He then commanded a servant to pace out a

FIGURE 1.6 Over 2,000 years ago, Eratosthenes calculated the circumference of the Earth using simple geometry.



Eratosthene's calculation:

$$\frac{360°}{x} = \frac{7.2°}{5{,}000 \text{ stadia}}$$

$$x = \frac{360° \times 5{,}000 \text{ stadia}}{7.2°}$$

$$x = 250{,}000 \text{ stadia}$$

250,000 stadia × 0.1572 km/stadium = 39,300 km (or, 24,421 miles)

straight line from Alexandria to Syene. The sore-footed servant found the distance to be 5,000 stadia (1 stadium = 0.1572 km). Knowing that a circle contains 360°, Eratosthenes then calculated the Earth's circumference using a simple equation, and his answer came within 2% of today's accepted value of 40,008 km (24,865 miles).

Not long after Eratosthenes' discovery, Greek mathematicians used ingenious geometric calculations to estimate that the distance to the Moon is about 30 times the Earth's diameter. This number comes close to the true distance, which on average is 381,555 km (about 237,100 miles). But it wasn't until the 17th century that astronomers figured out that the mean distance between the Earth and the Sun is 149,600,000 km (about 93,000,000 miles). As for the stars, the ancient Greeks realized that they must be much farther away than the Sun in order for them to appear as a fixed backdrop behind the Moon and planets, but the Greeks had no way of calculating the actual distance. Our modern documentation of the vastness of the Universe began in 1838, when astronomers determined that the nearest star to Earth, Alpha Centauri, lies 40.85 trillion km away.

Did you ever wonder . . .

how far away the stars are?

When researchers discovered that light travels at a constant speed of about 300,000 km (about 186,000 miles) per second in space, astronomers realized that they had a convenient way to describe the huge distances between objects in space. They defined a large distance by stating how long it takes for light to traverse that distance. For example, it takes light about 1.3 seconds to travel from the Earth to the Moon, so we can say that the Moon is about 1.3 light seconds away. Similarly, we can say that the Sun is 8.3 light minutes away. A **light year**, the distance that light travels in one Earth year, is about 9.5 trillion km (about 6 trillion miles). When you look up at Alpha Centauri, 4.37 light years distant, you see light that started on its journey to Earth 4.37 light years ago.

Astronomers didn't develop techniques for measuring the distance to very distant stars and galaxies until the 20th century. With these techniques (described in astronomy books), they determined that the Milky Way itself is about 100,000 light years across. Other galaxies are so far away that, to the naked eye, they look like stars in the night sky. The nearest spiral galaxy to ours, Andromeda, lies 2.2 million light years away. The farthest celestial objects that can be seen with the naked eye are less than 3 million light years away. Light from these objects that we see today started on its path to Earth a million years before the first hominids (direct human ancestors) walked the Earth. Powerful telescopes allow us to see much farther. The edge of the visible Universe lies over 13 billion light years away. When such numbers became known, people came to the realization that the dimensions of the Universe are truly staggering!

It's hard to fathom the distances to planets and stars without visualizing more familiar objects. Imagine a *scale model* (a model in which dimensions are shrunk in proper proportion) in which the Sun is the size of an orange. At this scale, the Earth would be a sesame seed at a distance of 15 m (49 ft) from the orange, and Alpha Centauri would lie 2,000 km (about 1,243 miles) from the orange.

Motions of the Heavens

As you sit in your chair reading this book, you may think that you are motionless, but you aren't. It just seems that way because everything in the room around you is moving at exactly the same velocity as you are. Relative to an observer in intergalactic space, in fact, you're moving quite fast!

Let's consider the components of this motion. First of all, the Earth, like all planets, rotates or "spins" on its *axis*, the imaginary line that passes through the center of the Earth and pierces the planet's surface at its two poles. Earth's axis currently tilts at about 23.4° relative to the ecliptic. Because of this rotation, a person sitting on the **equator** (the circumference on the surface of the Earth, at a distance halfway between the poles) is moving at about 1,674 km per hour (1,040 mph)—faster than the speed of sound! It is due to this spin that the Sun and stars appear to cross the sky daily (Box 1.2).

Did you ever wonder . . .

how fast you are traveling through space?

The Earth also orbits the Sun, traveling counterclockwise along a 150 million km-long elliptical path that takes a full year to complete—it moves along this orbit at about 30 km per second (108,000 km per hour). And finally, the whole Solar System revolves around the center of the Milky Way about once every 250 million years, so we hurtle through space, relative to an observer standing outside the Milky Way, at about 200 km per second (720,000 km per hour).

Take-Home Message

People once thought the Earth lay at the center of the Universe. Now it's clear that it is one of eight spinning planets orbiting our Sun, one of 300 billion stars of the revolving, spiral-shaped Milky Way galaxy. Hundreds of billions of galaxies speckle the immense visible Universe.

QUICK QUESTION: Imagine that the distance between the Sun and Alpha Centauri is represented by the length of a city bus. At this scale, what is the diameter of the Milky Way?

BOX 1.2 CONSIDER THIS . . .

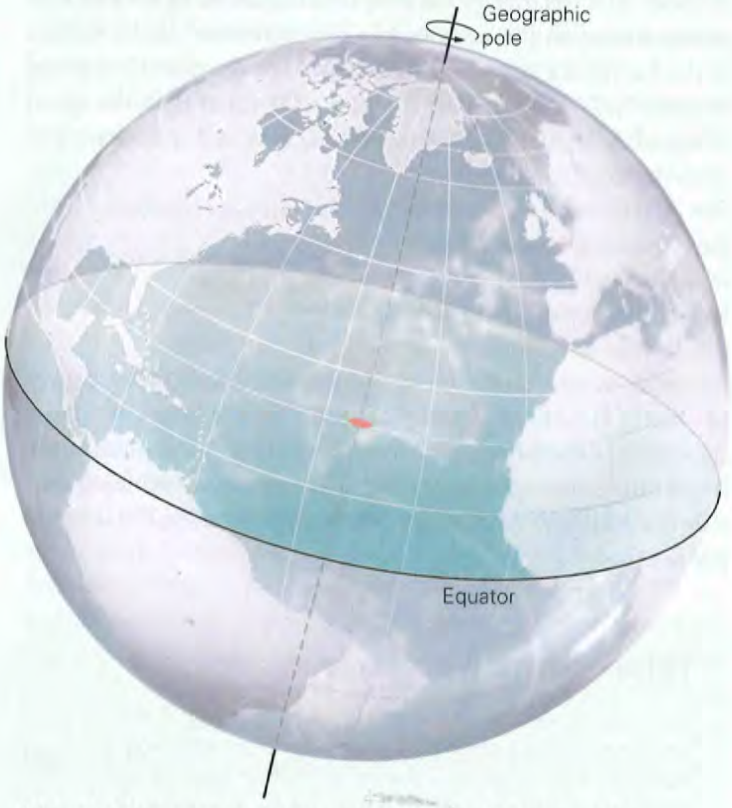
How Do We Know That the Earth Rotates?

How do we know that the Earth spins around its axis? The answer comes from observing the apparent motion of the stars (**Fig. Bx1.2a**). If you're in the northern hemisphere (i.e., north of the equator) and gaze at the night sky for many hours, you'll see the stars move in a circular path around the "North Star," which is currently Polaris.

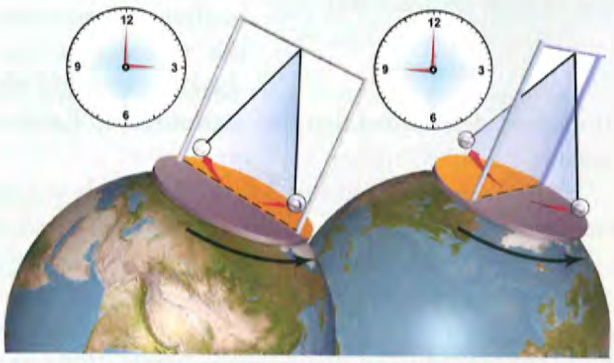
Curiously, it wasn't until the middle of the 19th century that Léon Foucault (1819–68), a French physicist, actually proved that the Earth spins on its axis. He made this discovery by setting a heavy pendulum, attached to a long cable, in motion (**Fig. Bx1.2b**). As the pendulum continued to swing, Foucault noted that the plane in which it oscillated was perpendicular to the Earth's surface and that this plane rotated around a vertical axis. If Newton's first law of motion—objects in motion remain in motion and objects at rest remain at rest—was correct, this phenomenon meant that the Earth was rotating under the pendulum while the pendulum continued to swing in the same plane (**Fig. Bx1.2c**). Foucault displayed his discovery beneath the great dome of the Pantheon in Paris, to much acclaim.

We now know that the Earth's spin axis is not perfectly fixed in orientation; rather, it wobbles. This wobble, known as precession, is like the wobble of a toy top as it spins. As a result, Polaris isn't always the North Star. We'll see later in this book that the precession of the Earth's axis, which takes 23,000 years, may affect the planet's climate.

FIGURE Bx1.2 Proving the Earth rotates on its axis.



(a) The Earth is a sphere rotating around an axis. The axis, which pierces the Earth at the poles and goes through the center of the planet, is tilted relative to the ecliptic of the Earth's orbit.



(b) Foucault's experiment. At Time 1, the plane in which the pendulum swings is the same as the plane of the frame. At Time 2, six hours later, the plane in which the pendulum swings is perpendicular to the plane of its frame.

(c) An exact replica of Foucault's original pendulum on display in the Panthéon, Paris.

1.3 Forming the Universe

We stand on a planet, in orbit around a star, speeding through space on the arm of a galaxy. Beyond our galaxy lie hundreds of billions of other galaxies. Where did all this "stuff"—the matter of the Universe—come from, and when did it first form? For most of human history, a scientific solution to these questions seemed intractable. But in the 1920s, unexpected observations about the nature of light from distant galaxies set astronomers on a path of discovery that ultimately led to a scientific model of Universe formation known as the *Big Bang theory*, and this idea has become the foundation of scientific cosmology. To explain these observations, we must first introduce an important phenomenon called the Doppler effect. Thus, we begin this section by developing an understanding of how the Doppler effect modifies the light seen in telescopes. We then show how this understanding leads to the idea that the Universe expands, and then to the conclusion that this expansion began during the Big Bang.

Waves and the Doppler Effect

When a train whistle screams, the sound you hear moved through the air from the whistle to your ear in the form of sound waves. *Waves* are disturbances that transmit energy from one point to another in the form of periodic motions. You're probably most familiar with water waves. As such waves pass, the surface of the water goes up and down in a direction perpendicular to the direction the wave moves. The ups form *crests*, and the downs form *troughs*. Sound waves are different. As a sound wave passes, air moves back and forth, alternately compressing and expanding. The whistle sound is not just one wave but rather is a succession of many waves. We refer to the distance between successive waves as the *wavelength* and the number of waves that pass a point in a given time interval as the **frequency**. If the wavelength decreases, more waves pass a point in a given time interval, so the frequency increases. The "pitch" of a sound, its note on the musical scale, depends on the frequency of the sound waves.

Now imagine that you are standing on a station platform, and a train moves toward you. The train whistle's sound gets louder as the train approaches, but its pitch remains the same. Then, the instant the train passes, the pitch abruptly changes—it sounds like a lower note in the musical scale. Why? When the train moves toward you, the sound has a higher frequency (the waves are closer together, so the wavelength is smaller) because the sound source, the whistle, has moved slightly closer to you between the instant that it emits one wave and the instant that it emits the next (Fig. 1.7a, b). When the train moves away from you, the sound has a lower frequency (the waves are farther apart) because the whistle has moved slightly farther from you between the instant it emits one wave and the instant it emits the next. An Austrian physicist, C. J. Doppler (1803–53), first explained this phenomenon, and thus the change in frequency that happens when a wave source moves is now known as the **Doppler effect**.

Light energy also moves in the form of waves. Physicists consider light to be a form of **electromagnetic radiation**, energy that can be released by hot or glowing objects and can be transmitted through a vacuum. We can represent light waves symbolically by a periodic succession of crests and troughs, which shape-wise resemble water waves but are otherwise very different in character. Visible light comes in many colors—the colors of the rainbow. The color you see depends on the frequency of the light waves, just as a sound you hear depends on the pitch of the frequency of sound waves. Specifically, red light has a longer wavelength (lower frequency) than does blue light.

The Doppler effect also applies to light but can be noticed only if the light source moves very fast, at least a few percent of the speed of light. If a light source moves away from you, the light you see becomes redder, as the light shifts to longer wavelength or lower frequency. If the source moves toward you, the light you see becomes bluer, as the light shifts to higher frequency. We call these changes the **red shift** and the **blue shift**, respectively (Fig. 1.7c).

Does the Size of the Universe Change?

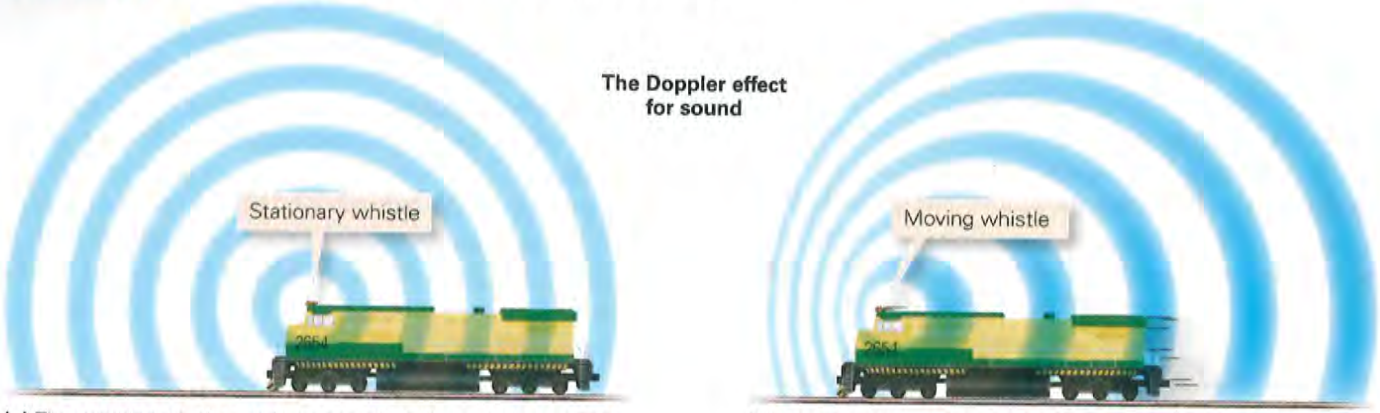
In the 1920s, astronomers such as Edwin Hubble, after whom the Hubble Space Telescope was named, braved many a frosty night beneath the open dome of a mountaintop observatory in order to aim telescopes into deep space. These researchers were searching for distant galaxies. At first, they only wanted to document the location and shape of newly discovered galaxies. Eventually, however, they also began to study the wavelength of light produced by the distant galaxies. The results yielded a surprise that would forever change humanity's perception of the Universe. To their amazement, astronomers found that the light coming to the Earth from distant galaxies displayed a red shift, relative to the light coming from nearby stars (Fig. 1.7d).

Around 1929, Hubble concluded that the red shift must be a consequence of the Doppler effect, and so galaxies exhibiting a red shift must be moving away from Earth at an immense velocity. At the time of Hubble's discovery, astronomers thought the Universe had a fixed size,

Did you ever wonder . . .

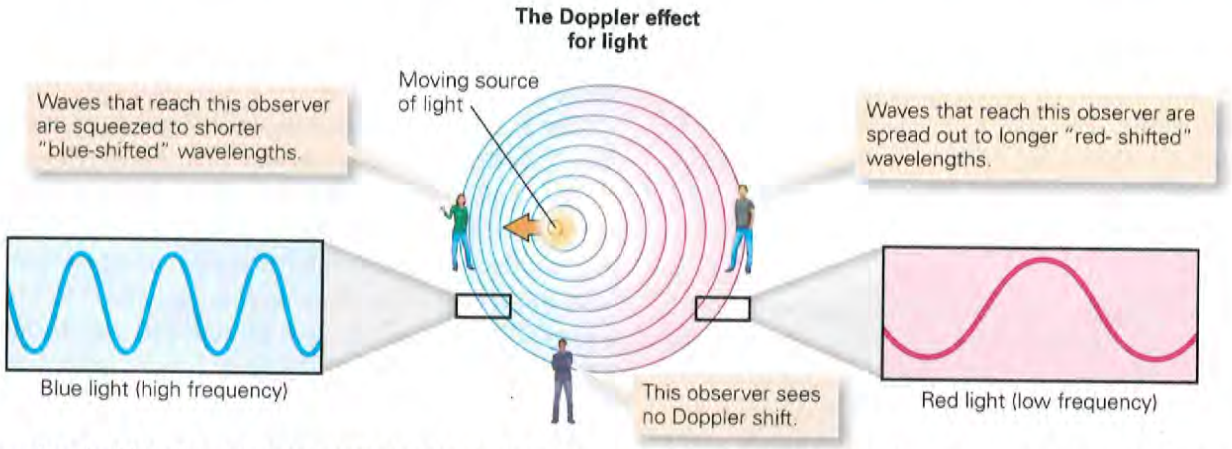
if galaxies move?

FIGURE 1.7 Manifestations of the Doppler effect for sound and for light.

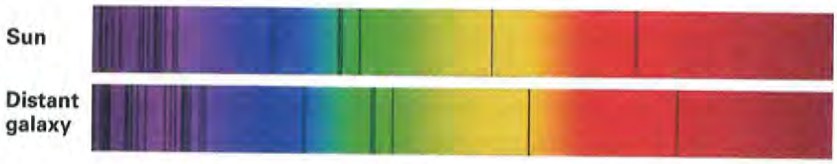


(a) The wavelength of sound waves emitted by a stationary train is the same in all directions.

(b) Waves behind a moving train have a longer wavelength than those in front.



(c) The wavelength of blue light is less than that of red light. If a light source moves very fast, the Doppler effect results in a shifting of the wavelengths. The observed shift depends on the position of the observer.

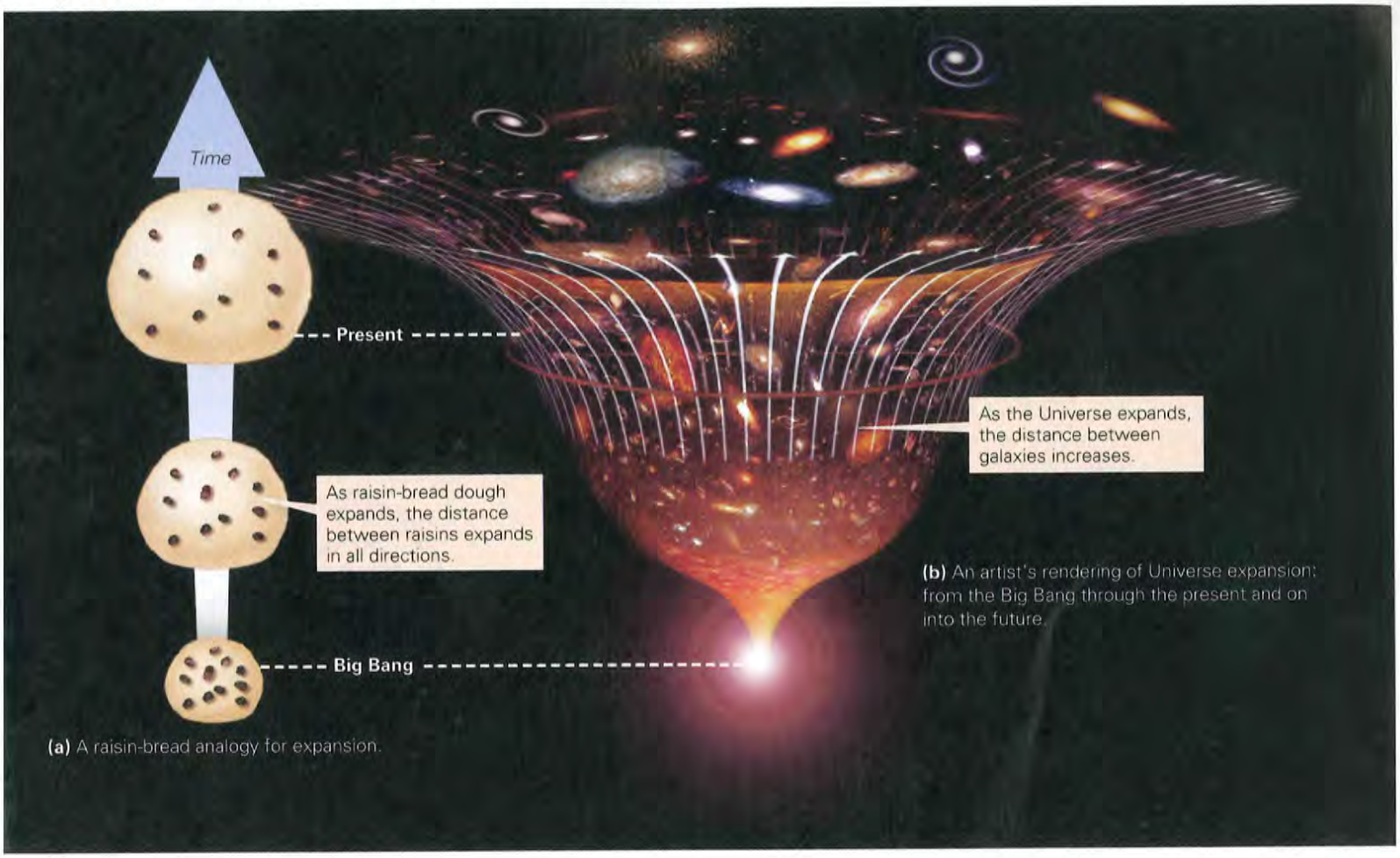


(d) The atoms in a star absorb certain specific wavelengths of light. We see these wavelengths as dark lines on a light spectrum. Note that the lines from a galaxy a billion light years away are shifted toward the red end of the spectrum (i.e., to the right), in comparison to the lines from our own Sun.

so Hubble initially assumed that if some galaxies were moving away from Earth, others must be moving toward Earth. But none could be found. The light from all distant galaxies, regardless of their direction from Earth, exhibits a red shift. In other words, all distant galaxies are moving rapidly away from us!

How can all galaxies be moving away from us, regardless of which direction we look? Hubble puzzled over this question and finally recognized the solution: the whole Universe must be expanding! This idea came to be known as the **expanding Universe theory.** To picture the expanding Universe, imagine a ball of bread dough with raisins scattered throughout. As the dough bakes and expands into a loaf, each raisin moves away from its neighbors, in every direction (Fig. 1.8a). Note that if two raisins were originally 1 cm apart, after a given time interval they spread to 2 cm apart and that during the same time interval raisins that were originally 4 cm apart become 8 cm apart—so the farther apart the raisins are to start with, the faster they move apart. By this analogy, galaxies that are farther away from the Earth are moving away from us faster than are galaxies closer to us, so farther galaxies exhibit a greater red shift than do nearer ones.

FIGURE 1.8 The concept of the expanding Universe and the Big Bang.



(a) A raisin-bread analogy for expansion.

(b) An artist's rendering of Universe expansion: from the Big Bang through the present and on into the future.

The Big Bang

Hubble's ideas started a revolution in cosmological thinking. Now we picture the Universe as an expanding bubble, in which galaxies race away from each other at incredible speeds. This image immediately triggers a key question of cosmology: Did the expansion begin at some specific time in the past? If it did, then that instant would mark the physical beginning of the Universe, the beginning of our space and time.

Most astronomers have concluded that expansion did indeed begin at a specific time, with a cataclysmic explosion called the Big Bang. According to the **Big Bang theory**, all matter and energy—everything that now constitutes the Universe—was initially packed into an infinitesimally small point, called a "singularity." The point exploded and the Universe began, according to current estimates, 13.7 (±1%) Ga (billion years ago).

Of course, no one was present at the instant of the Big Bang, so no one actually saw it happen. But by combining clever calculations with careful observations, researchers have developed a consistent model of how the Universe evolved, beginning an instant after the explosion (**Fig. 1.8b**). According to this model, the Universe was so small, so dense, and so hot during the first instants of its existence that it consisted entirely of energy—atoms, or even the smallest subatomic particles that make up atoms, could not even exist. (See **Box 1.3** for a review of atoms and molecules.) Within a few seconds of cooling, however, hydrogen atoms could begin to form. And by the time the Universe reached an age of 3 minutes, when its temperature had fallen below 1 billion degrees and its diameter had grown to about 53 million km (35 million miles), hydrogen atoms could fuse together to form helium atoms. Formation of new nuclei in the first few minutes of time is called **Big Bang nucleosynthesis** because it happened before any stars existed. This process could produce only small atoms, meaning ones containing a small number of protons (an atomic number less than 5), and it happened very rapidly. In fact, virtually all of the new atomic nuclei consisted of hydrogen and helium, and all of these atoms existed by the end of the first 5 minutes.

BOX 1.3 SCIENCE TOOLBOX . . .

Atoms, Molecules, and the Energy They Contain

What does matter consist of? A Greek philosopher named Democritus (ca. 460–370 B.C.E.) thought that if you could keep dividing a volume of matter into progressively smaller pieces, you would eventually end up with nothing, but that since it's not possible to make something out of nothing, there must be a smallest piece of matter that can't be subdivided further. He proposed the name *atom* for these smallest pieces, from the Greek word *atomos*, which means indivisible.

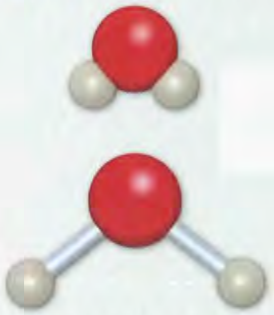
Our modern understanding of matter developed in the 17th century, when *chemists* (scientists who study the properties, composition, and behavior of matter) recognized that certain substances, such as hydrogen and oxygen, cannot break down into other substances, whereas some substances, such as water and salt, can break down. The former came to be known as **elements**, and the latter came to be known as **compounds**. John Dalton (1766–1844) adopted the word *atom* for the smallest piece of an element that has the property of the element; the smallest piece of a compound that has the properties of the compound is a *molecule*. In 1869, Dmitri Mendeleev (1834–1907) recognized that groups of elements share similar characteristics, and he organized the elements into a chart that we now call the *periodic table* of the elements (see Appendix). The bonds holding atoms together in a molecule are called **chemical bonds**, which we discuss further in Chapter 5 As an example, chemical bonds hold two hydrogen atoms to form an H_2 molecule, and two hydrogen atoms plus an oxygen atom together form an H_2O (water) molecule (**Fig. Bx1.3a**).

During a **chemical reaction**, chemical bonds break and/or form, so atoms can separate from one another and can recombine in new molecules. *Chemical energy* is the potential energy stored in chemical bonds that can be released during a chemical reaction.

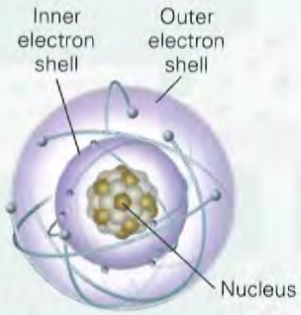
The vibration and movement of atoms and molecules produces thermal energy. Put another way, *thermal energy*, or *heat*, is the total kinetic energy contained in a material due to the motion of its particles. *Temperature* represents the average velocity particle movements and thus is a measure of hot and cold. The faster the particles are moving, the higher the temperature. We use a variety of scales—the Celsius scale in the metric system, and the Fahrenheit in the English system—to represent temperature. Water freezes at 0°C, or 32°F, and boils at 100°C, or 212°F.

Chemists in the 17th and 18th centuries identified 92 naturally occurring elements on Earth; physicists have created more than a dozen new ones. Each element has a name and a symbol (e.g., N = nitrogen; H = hydrogen; Fe = iron; Ag = silver). In

FIGURE Bx1.3 The nature of atoms.



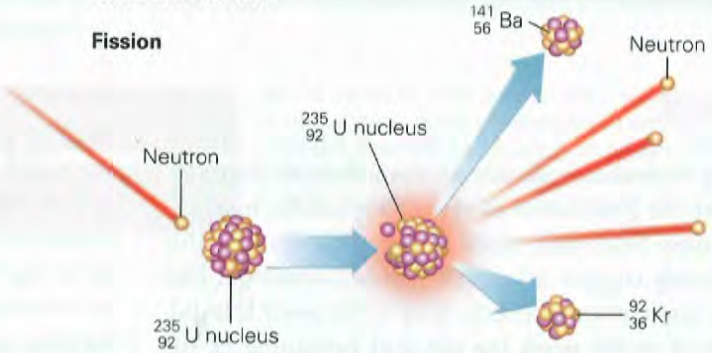
(a) Two ways of portraying a water molecule. The red ball is oxygen; the small balls are hydrogen.



(b) An image of an atom with a nucleus orbited by electrons.

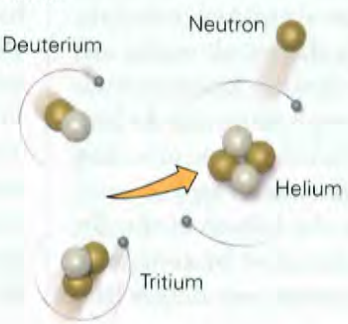
Nuclear Reactions

Fission



(c) A uranium atom splits during nuclear fission.

Fusion



(d) Two atoms (versions of hydrogen) stick together to form one atom of helium during nuclear fusion in a hydrogen bomb.

1910, Ernest Rutherford, a British physicist, proved that, contrary to the view of Democritus, atoms actually can be divided into smaller pieces. Most of the mass in an atom clusters in a dense ball, called the *nucleus*, at the atom's center. The nucleus contains two types of subatomic particles: *neutrons*, which have a neutral electrical charge, and *protons*, which have a positive charge. A cloud of electrons surrounds the nucleus (**Fig. Bx1.3b**); an *electron* has a negative charge and contains only 1/1,836 as much mass as a proton. (*Charge*, simplistically, refers to the way in which a particle responds to a magnet or an electric current; unlike charges attract, while like charges repel).

Electron clouds have a complex internal structure—electrons are grouped into intervals called orbitals, energy levels, or *electron shells*. Electrons in inner shells concentrate closer to the nucleus, and those in outer shells are farther away. Roughly speaking, the diameter of an electron cloud is 10,000 times greater than that of the nucleus, yet the cloud contains only 0.05% of an atom's mass—thus, atoms are mostly empty space! Electrons in an orbital store potential energy, so when they move from one orbital to another, they release or absorb energy. Electromagnetic energy can drive this movement.

We distinguish atoms of different elements from one another by their *atomic number*, the number of protons in their nucleus. Smaller atoms have smaller atomic numbers, and larger ones have larger atomic numbers. The smallest atom, hydrogen, has an atomic number of 1, and the largest naturally occurring atom, uranium, has an atomic number of 92. Except for hydrogen nuclei, all nuclei also contain neutrons. In smaller atoms, the number of neutrons roughly equals the number of protons, but in larger atoms the number of neutrons exceeds the number of protons. The *atomic mass* of an atom is roughly the sum of the number of neutrons and the number of protons. For example, an oxygen nucleus contains 8 protons and 8 neutrons and thus has an atomic mass of 16.

The bonds holding subatomic particles in the nucleus, called *nuclear bonds*, store potential energy. Atoms can change only during *nuclear reactions*, when nuclear bonds break or form. Physicists recognize several types of nuclear reactions. For example, during *fission*, a large nucleus breaks apart to form two smaller atoms. Fission generates energy in nuclear power plants and in the explosion of an atomic bomb. During *fusion*, two smaller atoms come together to form a larger atom. Fusion reactions power the Sun and occur during the explosion of a hydrogen bomb (**Fig. Bx1.3c, d**).

Matter can exist in different forms depending on the degree to which the atoms are bonded together. These are called *states of matter* (discussed further in Chapter 5). A material in which all the atoms or molecules are bonded tightly together is a *solid*; solids can hold their shape and can't flow easily. A material in which the atoms are not held together so well and occur in disorganized clumps or chains that can flow past each other is a *liquid*; though a liquid can flow, it stays together in a confined volume. In a *gas*, atoms or molecules are not bonded to each other at all but rather move around rapidly in all directions; thus, a gas expands to fill any container it's placed in, completely. A substance can change state. For example, during *condensation*, a gas becomes a liquid and during *freezing*, a liquid becomes a solid.

Now that we've reviewed the basic structure of matter, we can quickly return to the discussion of energy that we started in Box 1.1. There are many types of energy that can be understood in the context of the behavior of matter, such as *thermal energy* or *heat* and *chemical energy*, as defined above. Also, nuclear reactions yield *nuclear energy* because when nuclear bonds break, a small amount of matter converts into energy following the famous equation $E = mc^2$, introduced by Albert Einstein (1879–1955); in this equation, E stands for energy, m stands for mass, and c stands for the speed of light.

The matter and energy that we've just discussed, according to calculations by physicists, accounts for only a small portion (4.6%) of the whole universe. The remainder consists of mysterious *dark matter* and *dark energy*. They are called dark because we cannot see them.

Eventually, the Universe cooled enough for chemical bonds to bind atoms together in molecules. Most notably, hydrogen atoms bonded to form molecular hydrogen (H_2). As the Universe expanded and cooled further, atoms and molecules slowed down and accumulated into patchy clouds called **nebulae.** The earliest nebulae of the Universe consisted almost entirely of hydrogen and helium gas.

Birth of the First Stars

When the Universe reached its 200 millionth birthday, it contained immense, slowly swirling, dark nebulae separated by vast voids of empty space (Fig. 1.9). The Universe could not remain this way forever, though, because of the invisible but persistent pull of gravity. Eventually, gravity began to remold the Universe pervasively and permanently.

All matter exerts gravitational pull—a type of force—on its surroundings, and as Isaac Newton first pointed out, the amount of pull depends on the amount of mass. Somewhere in the young Universe, the gravitational pull of an initially more massive region of a nebula began to suck in surrounding gas and, in a grand example of the rich getting richer, grew in mass and therefore **density** (mass per unit volume). As this denser region attracted progressively more gas, the gas compacted into a smaller region, and the initial swirling movement of gas transformed into a rotation around an axis. As gas continued to move inward, cramming into a progressively smaller volume, the rotation rate became faster and faster. (A similar phenomenon happens when a spinning ice skater pulls her arms inward.) Because of its increased rotation, the nebula evolved into a disk shape. As more and more matter rained down onto the disk, it continued to grow, until eventually, gravity collapsed the inner

FIGURE 1.9 A representation of a starless nebula in the early Universe. This rendition is modified from a Hubble Space Telescope photograph.

portion of the disk into a dense ball. As the gas was compressed into a smaller and smaller space, its temperature increased dramatically. Eventually, the central ball of the disk became hot enough to glow, and at this point it became a **protostar**. The remaining mass of the disk, as we will see, eventually clumped into smaller spheres, the planets.

A protostar continues to grow, by pulling in successively more mass, until its core becomes extremely dense and its temperature reaches about 10,000,000°C. Under such conditions, hydrogen nuclei slam together so forcefully that they undergo a series of fusion reactions, ultimately forming helium nuclei. Such fusion reactions produce huge amounts of energy, and the mass becomes a fearsome furnace. When the first nuclear fusion reactions began in the first protostar, the body "ignited" and the first true star formed. When this happened, perhaps 800 million years after the Big Bang, the first starlight illuminated the newborn Universe. This process would soon happen again and again, and many *first-generation stars* came into existence.

First-generation stars tended to be very massive, perhaps 100 times the mass of the Sun. Astronomers have shown that the larger the star, the hotter it burns and the faster it runs out of fuel and dies. A huge star may survive only a few million years to a few tens of millions of years before it explodes. The explosion of a giant star produces a *supernova* (from the Latin word *nova*, meaning new), so named because closer examples can be seen from Earth, where they appear as "new" stars in the sky. Thus, not long after the first generation of stars formed, the Universe began to be peppered with the first generation of supernovae.

Take-Home Message

Study of the red shift shows that all distant galaxies are moving away from us, an observation that requires the Universe to be expanding. According to the Big Bang theory, this expansion, and thus the beginning of our Universe, began with a cataclysmic explosion at 13.7 Ga. Atoms formed during the Big Bang collected into nebulae which, due to gravity, collapsed into dense balls that began to produce energy by nuclear fusion reactions. These objects were the first stars.

QUICK QUESTION: The farther a galaxy lies from the Earth, the greater the red shift it exhibits. Why?

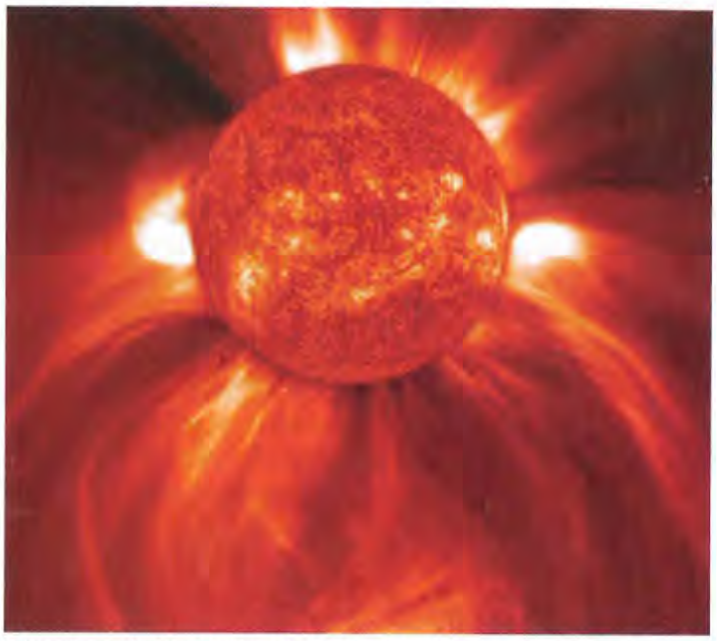
1.4 We Are All Made of Stardust

Where Do Elements Come From?

Nebulae from which the first-generation stars formed consisted entirely of small atoms (atoms with atomic numbers less than 5) because only these small atoms were generated by Big Bang nucleosynthesis. In contrast, the Universe of today contains 92 naturally occurring elements. Where did the other 87 elements come from? In other words, how did such as carbon, sulfur, silicon, iron, gold, and uranium form? These elements, which are common on Earth, have atomic numbers that are greater than 5. For example, carbon has an atomic number of 6, and iron has an atomic number of 26. Physicists have shown that these elements form during the life cycle of stars, by the process of **stellar nucleosynthesis**. Because of stellar nucleosynthesis we can consider stars to be "element factories," constantly fashioning larger atoms out of smaller atoms.

What happens to the atoms produced by stellar nucleosynthesis? Some escape into space during the star's lifetime, simply by moving fast enough to overcome the star's gravitational pull. The stream of atoms emitted from a star during its lifetime is a **stellar wind** (Fig. 1.10a). Most escape only when a star dies. A low-mass star (like our Sun) releases a large shell of gas as it dies, ballooning into a *red giant* during the process, whereas a high-mass star blasts matter into space during a supernova explosion (Fig. 1.10b). Most very large atoms (those with atomic numbers greater than that of iron) require even more violent circumstances to form than generally occurs

FIGURE 1.10 Element factories in space.



(a) A photo of solar (stellar) wind streaming into space.

(b) Very heavy elements form during supernova explosions. Here we see the rapidly expanding shell of gas ejected into space from an explosion whose light reached the Earth in 1054 C.E. This shell is called the Crab Nebula.

within a star. In fact, most very large atoms form by *supernova nucleogenesis*, which takes place in the inconceivable heat of a supernova explosion.

When the first generation of stars died, it left a legacy of new, heavier elements that then mixed with residual gas from the Big Bang. A second generation of stars and associated planets formed out of these compositionally more diverse nebulae. Second-generation stars lived and died and contributed heavier elements to third-generation stars. Succeeding generations contain a greater proportion of heavier elements. (Nevertheless, most of the visible mass of the Universe still consists of 74% hydrogen and 24% helium.) Because not all stars live for the same duration of time, at any given moment the Universe contains many different generations of stars. Our Sun may be a third-, fourth-, or fifth-generation star. Thus, the mix of elements we find on Earth includes relicts of primordial gas from the Big Bang as well as the disgorged guts of dead stars. Think of it—the elements that make up your body once resided inside a star! The proportions of elements reflect the processes of element formation and the degree to which stellar gases and supernova gases mix in (Table 1.1).

Did you ever wonder . . .

where the atoms in your body first formed?

The Nebular Theory for Forming the Solar System

Earlier in this chapter, we introduced scientific concepts of how stars form from nebulae that consisted mostly of small atoms formed by Big Bang nucleosynthesis. But we delayed addressing the question of how the planets and other objects in our Solar System originated until we had discussed the production of heavier elements, such as oxygen, silicon, and iron, because planets such as the Earth consist predominantly of these elements. Now that we've shown how stars and supernovae can

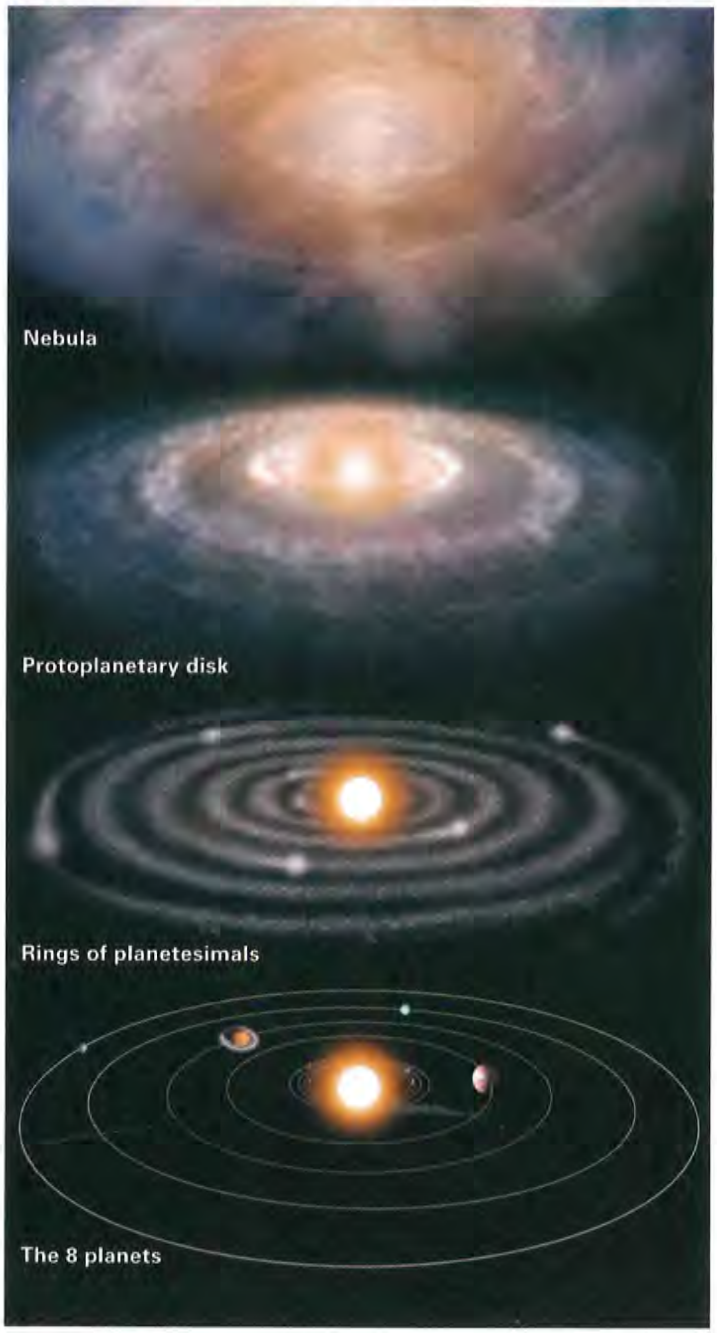
TABLE 1.1 Top 10 Elements in the Milky Way (out of 1 Million Atoms)

Hydrogen	739,000
Helium	240,000
Oxygen	10,400
Carbon	4,600
Neon	1,340
Iron	1,090
Nitrogen	960
Silicon	650
Magnesium	580
Sulfur	440
Other (approx.)	940

serve as element factories for larger atoms, we return to the early history of the Solar System and add an explanation for the origin of planets, moons, asteroids, and comets.

In the context of scientific cosmology, the Sun and all other objects in the Solar System formed from material that had been swirling about in a nebula, an idea now known as the **nebular theory** (Fig. 1.11). According to the theory, the process of Solar System formation involved several stages (Geology at a Glance, pp. 30–31). First, as we've seen, a swirling nebula coalesces into a spinning disk with a bulbous center. The central "bulb" of this disk became the Sun, whereas the remainder of the Solar System formed from the material in the flattened outer part of the disk, a region now known as the **protoplanetary disk**.

FIGURE 1.11 Nebular theory for planet formation.

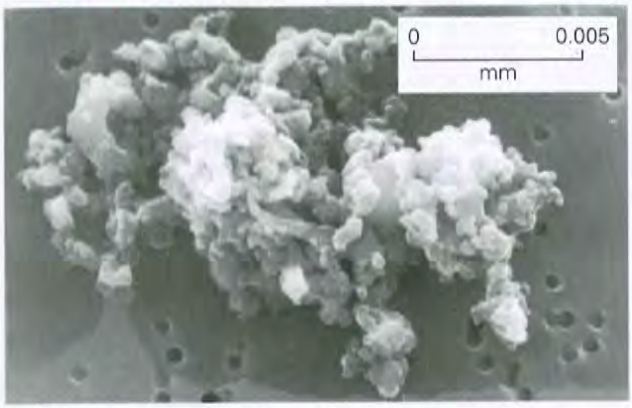


The protoplanetary disk contained all 92 elements, some as isolated atoms and some bonded to others in molecules, a mixture of gases produced during the Big Bang as well as gases expelled from earlier generations of stars and from supernova explosions. Geologists divide the materials formed from these atoms and molecules into two classes. **Volatile materials**—such as hydrogen, helium, methane, ammonia, water, and carbon dioxide—can exist as gas at the Earth's surface. In the pressure and temperature conditions of space, all volatile materials remain in a gaseous state closer to the Sun. But beyond a distance called the *frost line*, volatiles can freeze to form into ice. (Note again that we don't limit use of the word *ice* for frozen water alone but instead use it for any frozen volatile material.) **Refractory materials** are those that melt only at high temperatures, and they solidify to form solid soot-sized particles of "dust" in the coldness of space. Some of this dust consisted mostly of metal, but a large portion of the dust formed in this way contains molecules of silicon and oxygen bonded to various metal atoms. We'll see in Chapter 5 that such materials are known as *silicate minerals* and that they form most of the rock of the Earth, so clumps of silicate-mineral dust were rock-like in character.

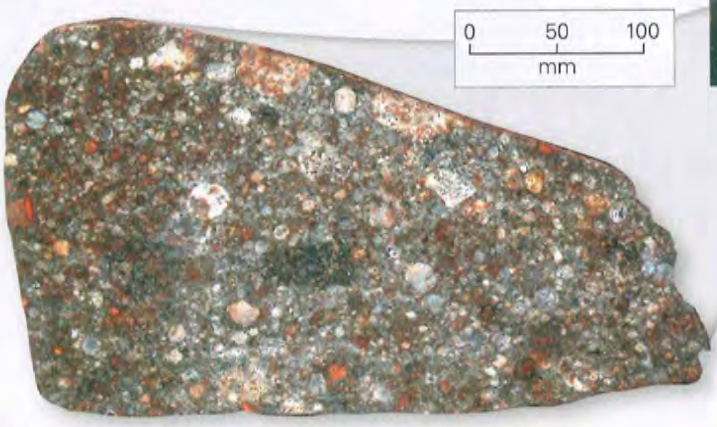
Initially, the protoplanetary disk may have been fairly homogeneous, meaning that it had much the same composition throughout, and most volatiles were frozen. But as the proto-Sun began to form, the inner part of the disk became hotter and the frost line moved outward. The volatile materials closer to the Sun evaporated, and when the Sun became a nuclear inferno, the *solar wind* (the stellar wind produced by our Sun) blew these materials to the outer portions of the disk. Thus, the inner part of the protoplanetary disk ended up with relatively higher concentrations of dust, whereas the outer portions ended up with relatively higher concentrations of ice. As this was happening, gravity caused the gas, dust, and ice of the disk to separate into a series of concentric rings in which density exceeded that of the space between the rings.

How did the dusty, icy, and gassy rings transform into planets? Even before the proto-Sun ignited, the material of the surrounding rings began to clump and bind together due to gravity (Fig 1.12). First, soot-sized particles merged into sand-sized grains. Then these grains stuck together to form grainy basketball-sized blocks, which in turn collided. If the collision was slow, blocks stuck together or simply bounced apart. If the collision was fast, one or both of the blocks shattered, producing smaller fragments that recombined later. Eventually, enough blocks coalesced to form **planetesimals**, solid

FIGURE 1.12 Forming solids in the Solar System.



(a) At first, solids collected into dust-sized aggregates.



(b) Eventually, the dust collected into grainy masses, similar to this meteorite fragment.

(c) The disk then evolved into a revolving ground of debris.

bodies whose diameter exceeded about 1 km. Because of their mass, planetesimals exerted enough gravity to attract and pull in other objects that were nearby. Figuratively, planetesimals acted like vacuum cleaners, sucking in small pieces of dust and ice as well as smaller planetesimals that lay in their orbit, and in the process they grew progressively larger—astronomers refer to this process of planetary growth as *accretion*. Eventually, victors in the competition to attract mass grew into **protoplanets**, bodies approaching the size of today's inner planets. Once a protoplanet succeeded in incorporating virtually all the debris within its orbit, it became a full-fledged planet.

Early stages in the planet-forming process probably occurred very quickly—some computer models suggest that it may have taken less than 1 million years to go from the dust-and-gas stage to the large planetesimal stage. Planets may have grown from planetesimals in 10 million to 200 million years. In the inner orbits, where rings of the protoplanetary disk consisted mostly of dust (refractory materials), small terrestrial planets composed mostly of rock and metal formed. The outer rings of the protoplanetary disk, in contrast, contained huge volumes of volatile materials. Protoplanets formed in the outer rings gathered up the volatile material to form the giant planets. Refractory materials that occur in these planets sank to the center, so these planets consist of a small refractory (metal and rock) ball, surrounding by very thick shells of volatile materials (in the form of gas, liquid, or ice).

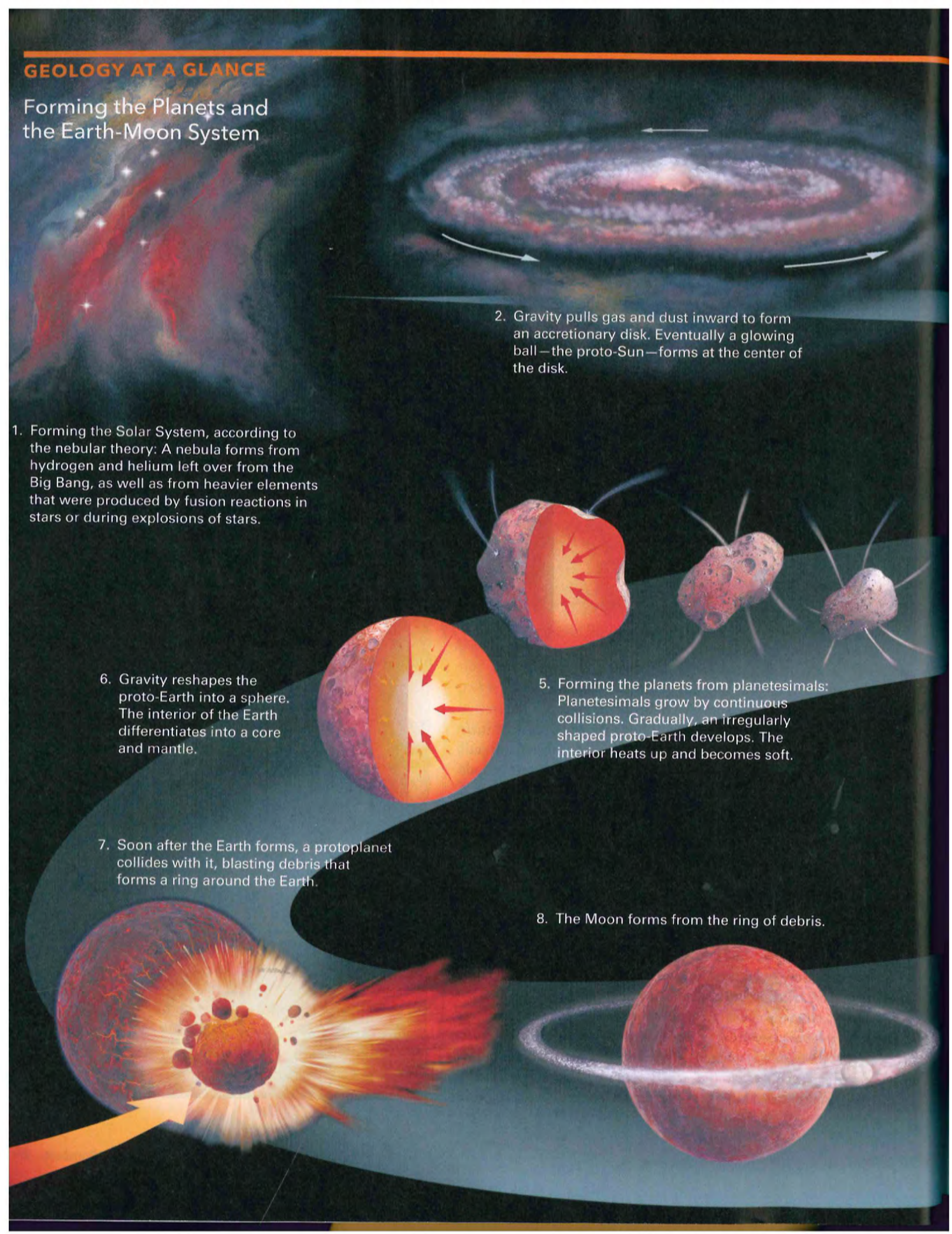
When did the planets form? As we'll discuss later in the book, rocks now exposed on the surface of the Earth are much younger than the Solar System. But certain *meteorites*, objects that fell to Earth from space (see Chapter 2), appear to be leftover planetesimals. Using dating techniques introduced in Chapter 12, geologists have determined that the materials comprising these meteorites formed at about 4.54 Ga and thus consider that date to be the birth date of the Solar System. If this date is correct, it means that the Solar System formed about 9 billion years after the Big Bang and thus is only about a third as old as the Universe.

Differentiation of the Earth and Formation of the Moon

When planetesimals first formed, they had a fairly homogeneous distribution of material throughout because the smaller pieces from which they formed all had much the same composition and collected together in no particular order. But large planetesimals did not stay homogeneous for long because they

GEOLOGY AT A GLANCE

Forming the Planets and the Earth-Moon System



1. Forming the Solar System, according to the nebular theory: A nebula forms from hydrogen and helium left over from the Big Bang, as well as from heavier elements that were produced by fusion reactions in stars or during explosions of stars.

2. Gravity pulls gas and dust inward to form an accretionary disk. Eventually a glowing ball—the proto-Sun—forms at the center of the disk.

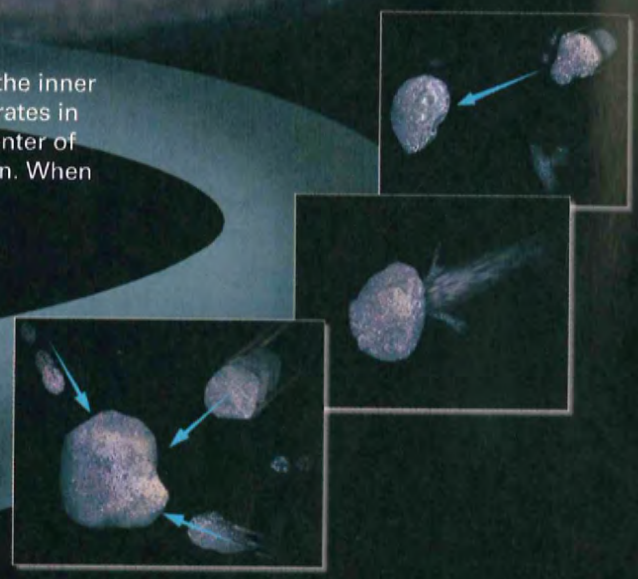
5. Forming the planets from planetesimals: Planetesimals grow by continuous collisions. Gradually, an irregularly shaped proto-Earth develops. The interior heats up and becomes soft.

6. Gravity reshapes the proto-Earth into a sphere. The interior of the Earth differentiates into a core and mantle.

7. Soon after the Earth forms, a protoplanet collides with it, blasting debris that forms a ring around the Earth.

8. The Moon forms from the ring of debris.

3. "Dust" (particles of refractory materials) concentrates in the inner rings, while "ice" (particles of volatile materials) concentrates in the outer rings. Eventually, the dense ball of gas at the center of the disk becomes hot enough for fusion reactions to begin. When it ignites, it becomes the Sun.



4. Dust and ice particles collide and stick together, forming planetesimals.

9. Eventually, the atmosphere develops from volcanic gases. When the Earth becomes cool enough, moisture condenses and rains to create the oceans. Some gases may be added by passing comets.

began to heat up. The heat came primarily from three sources: the heat produced during collisions (similar to the phenomenon that happens when you bang on a nail with a hammer and they both get warm); the heat produced when matter is squeezed into a smaller volume; and the heat produced from the decay of radioactive elements (similar to the heat produced by a nuclear reactor). In bodies whose temperature rose sufficiently to cause internal melting, denser metals (mostly iron) separated out and sank to the center of the body, whereas lighter rocky materials (mostly silicate minerals) remained in a shell surrounding the center. By this process, called **differentiation**, protoplanets and large planetesimals developed internal layering early in their history (Fig. 1.13). As we will see later, the central ball of metal constitutes the body's *core* and the outer, rocky shell constitutes its *mantle*.

In the early days of the Solar System, planets continued to be bombarded by meteorites even after the Sun had ignited and differentiation had occurred. Heavy bombardment in the early days of the Solar System pulverized the surfaces of planets and eventually left huge numbers of craters. Bombardment also contributed to heating the planets. Most geologists favor a model in which a particularly large collision between the Earth and a large planetesimal or protoplanet at about 4.53 Ga produced our Moon. Moon formation happened because the collision was so cataclysmic that much of the colliding body disintegrated and evaporated, along with a large part of the Earth's mantle. A ring of debris formed around the remaining, now-molten Earth. This ring quickly coalesced by accretion to form the Moon. When first formed, the Moon was much closer to the Earth than it is today. Of note, not all moons in the Solar System necessarily formed in this manner. Some may have been independent protoplanets or comets that were captured by a larger planet's gravity.

Did you ever wonder . . .

if the Moon is as old as the Earth?

Making the Earth Round

Small planetesimals were jagged or irregular in shape, and asteroids today have irregular shapes. Planets, on the other hand, are more or less spherical. Why? Simply put, when a protoplanet gets big enough, gravity can change its shape. To picture how, imagine a block of cheese warming in an oven. As the cheese gets softer and softer, gravity causes it to spread out in a pancake-like blob. This model shows that gravitational force alone can cause material to change shape if the material is soft enough. Now let's apply this model to planetary growth.

The rock composing a small planetesimal is cool and strong enough so that the force of gravity is not sufficient to cause the rock to flow. But once a planetesimal grows beyond a certain critical size (about 1,000 km in diameter), its interior becomes warm and soft enough to flow in response to gravity. As a consequence, protrusions are pulled inward toward the center, and indentations rise, so that the

SEE FOR YOURSELF . . .

Meteor Crater

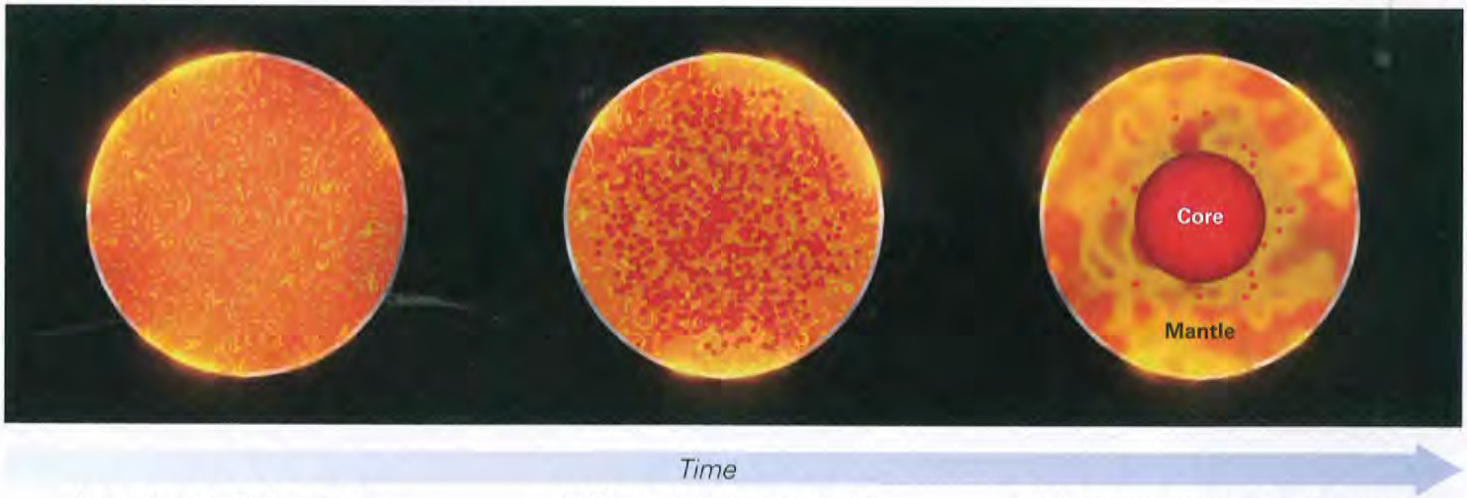
LATITUDE
35° 1'37.18"N

LONGITUDE
111° 1'20.17"W

Zoom to an elevation of 5.7 km (19,000 ft) and look straight down.

Some craters can be found on Earth. Meteor Crater, Arizona, is 1.1 km across.

FIGURE 1.13 Differentiation of the Earth's interior.



(a) Early on, the Earth was fairly homogeneous inside.

(b) When the temperature got hot enough, iron began to melt.

(c) The iron accumulated at the center of the planet to form a metallic core.

SEE FOR YOURSELF . . .

Manicouagan Crater

LATITUDE
51°19'50.07"N

LONGITUDE
68°40'59.96"W

Zoom to an elevation of 175 km (110 mi) and look straight down.

Manicouagan Crater of Quebec, Canada is 65 km across. The rim of the crater has filled with a lake.

planetesimal re-forms into a special shape—a sphere—that permits the force of gravity to be nearly the same at all points on its surface, for in a sphere mass is evenly distributed around the center.

Forming the Ocean and Atmosphere

Unlike the other terrestrial planets, the Earth today has an ocean of liquid water and an atmosphere that consists primarily of molecular nitrogen (N_2) and molecular oxygen (O_2). Where did the ocean and atmosphere come from? Let's take a brief look at how these entities, without which life as we know it could not exist, came to be.

When the Earth first formed, its atmosphere probably consisted mostly of molecular hydrogen and helium. But as the planet warmed, the temperature of these gases increased and the atoms were able to move so fast that, like rockets, they escaped the pull of gravity and were blown away from the Earth by the solar wind. Gradually, they were replaced by gases released from erupting volcanoes. These gases (volatile materials) were originally bonded to solid material of the Earth's mantle. But when portions of the mantle melted to produce molten rock that rose to the surface, the volatiles separated from the solids and bubbled out. Comets bombarding the Earth may have brought in additional gases. The atmosphere evolved into one consisting mostly of water, carbon dioxide (CO_2), ammonia, and methane—all gases released by "outgassing" of the interior. You would suffocate instantly if you were to breathe this early atmosphere.

When the Earth cooled sufficiently for water to condense (changing the state from gas to liquid), rain fell and the oceans accumulated. The concentration of water in the atmosphere decreased substantially as a consequence. The CO_2 from the atmosphere then dissolved in the water and precipitated into solids, which eventually became trapped in the crust as rock. Thus, the concentration of CO_2 diminished substantially. Because it does not react with other earth materials, N_2 remained in the atmosphere and eventually became the dominant component of the atmosphere. Only later, after the appearance of organisms capable of carrying out photosynthesis, an O_2-generating reaction, did molecular oxygen appear in the atmosphere. As discussed in Chapter 13, the concentration of O_2 did not become significant until 600 million years ago.

Take-Home Message

Heavier elements formed in stars and supernovae added to gases in nebulae from which new generations of stars formed. Planets formed from rings of dust and ice orbiting the stars, so we are all formed of stardust. As they formed, planets differentiated, with denser materials sinking to the center.

QUICK QUESTION: Why are the gas-giant planets further from the Sun than are the terrestrial planets?

CHAPTER SUMMARY

- The geocentric model of the Universe placed the Earth at the center of the Universe, with the planets and Sun orbiting around the Earth within a celestial sphere speckled with stars. The heliocentric model, which gained acceptance during the Renaissance, placed the Sun at the center.
- Eratosthenes was able to measure the size of the Earth in ancient times, but it was not until fairly recently that astronomers accurately determined the distances to the Sun, planets, and stars. Distances in the Universe are so large that they must be measured in light years.
- The Earth is one of eight planets orbiting the Sun, and this Solar System lies on the outer edge of a slowly revolving galaxy, the Milky Way, which is composed of about 300 billion stars. The Universe contains at least hundreds of billions of galaxies.
- The red shift of light from distant galaxies, a manifestation of the Doppler effect, indicates that all distant galaxies are moving away from the Earth. This observation leads to the expanding Universe theory. Most astronomers agree that this expansion began after the Big Bang, a cataclysmic explosion that occurred about 13.7 Ga.

- The first atoms (hydrogen and helium) of the Universe developed within minutes of the Big Bang. These atoms formed vast gas clouds called nebulae.
- Gravity caused clumps of gas in the nebulae to coalesce into revolving balls. As these balls of gas collapsed inward, they evolved into flattened disks with bulbous centers. The protostars at the center of these disks eventually became dense and hot enough that fusion reactions began in them. When this happened, they became true stars, emitting heat and light.
- Heavier elements form during fusion reactions in stars; the heaviest are mostly made during supernova explosions. The Earth and the life forms on it contain elements that could only have been produced during the life cycle of stars. Thus, we are all made of stardust.
- According to the nebular theory of planet formation, planets developed from the rings of gas and dust surrounding protostars. The gas and dust condensed into planetesimals, which then clumped together to form protoplanets and finally true planets. Inner rings became the terrestrial planets. Outer rings grew into giant planets.
- The Moon formed from debris ejected when a protoplanet collided with the Earth in the young Solar System.
- A planet assumes a near-spherical shape when it becomes so soft that gravity can smooth out irregularities.

GUIDE TERMS

asteroid (p. 18)
astronomer (p. 14)
Big Bang nucleosynthesis (p. 23)
Big Bang theory (p. 23)
blue shift (p. 21)
chemical bond (p. 24)
chemical reaction (p. 24)
celestial object (p. 13)
comet (p. 18)
compound (p. 24)
cosmology (p. 13)
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terrestrial planets (p. 18)
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volatile materials (p. 28)

REVIEW QUESTIONS

1. Why do planets appear to move with respect to stars?
2. Contrast the geocentric and heliocentric Universe concepts.
3. Describe how Foucault's pendulum demonstrates that the Earth is rotating on its axis.
4. How did Eratosthenes calculate the Earth's circumference?
5. Imagine you hear the main character in a low-budget science-fiction movie say he will "return ten light years from now." What's wrong with his usage of the term?
6. Describe how the Doppler effect works.
7. What does the red shift of the galaxies tell us about their motion with respect to the Earth?
8. What is the Big Bang, and when did it occur?
9. When did hydrogen and helium atoms form?
10. Where did heavier elements form?
11. Describe the steps in the formation of the Solar System according to the nebular theory.
12. Describe how the Moon was formed.
13. Why is the Earth round?

ON FURTHER THOUGHT

14. Look again at Figure 1.2b. The North Star, a particularly bright star, lies just about at the center of the circles of light tracked out by other stars. (a) What does this mean about the position of the North Star relative to Earth's spin axis? Why is it called the North Star? (b) Consider the wobble of Earth's axis. Will the North Star be in the same position in a photograph taken from the same location in the future? Why?
15. The horizon is the line separating sky from the Earth's surface. Consider the shape of the Earth. How does the distance from your eyes to the horizon change as your elevation above the ground increases? To answer this question, draw a semicircle to represent part of the Earth's surface; then draw a vertical tower up from the surface. With your ruler, draw a line from various elevations on the tower to where the line is tangent to the surface of the Earth. (A tangent is a line that touches a circle at one point and is perpendicular to a radius.)
16. Astronomers discovered that more-distant galaxies move away from the Earth more rapidly than do nearer ones. Why? To answer this question, make a model of the problem by drawing three equally spaced dots along a line; the dot at one end represents the Earth, and the other two represent galaxies. "Stretch" the line by drawing the line and dots again, but this time make the line twice as long. This stretching represents Universe expansion. Notice that the dots are now farther apart. Using the following equation for velocity (Velocity = Distance/Time)—if you pretend that it took 1 second to stretch the line (so Time = 1 second), measurement of the distance that each galaxy moved relative to the Earth allows you to calculate velocity.
17. Consider that the deaths of stars eject quantities of heavier elements into space and that these elements then become incorporated in nebulae from which the next generation of stars forms. Do you think that the ratio of heavier to lighter elements in, say, a sixth-generation star is larger or smaller than the ratio in a second-generation star? Why?

smartwork

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This chapter's Smartwork features:

- Labeling exercises on the correct relative positions of bodies in the Solar System.
- A visual exercise identifying the structure of an atom.
- In-depth questions on how the Doppler effect works.

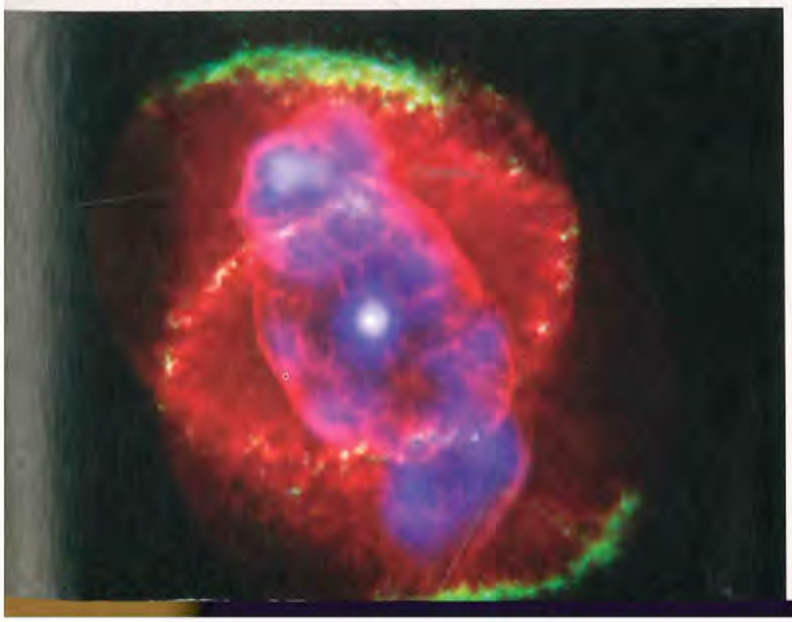
GEOTOURS

This chapter's GeoTour exercise (A) features:

- Nebular supernova
- Spiral galaxy
- Meteorite impacts

Another View

(a) The Cat's Eye Nebula is about 3,300 light years away. It formed when a dying star shed a shell of gas.



(b) The Andromeda Galaxy, 2.2 million light years away. It's about the same size as our own Milky Way.