

CHAPTER 1

The Earth in Context

1.1 Introduction

Sometime in the distant past, perhaps more than 50,000 generations ago, our ancestors 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 of all our surroundings—of our *Universe*. Questions that we ask about the Universe differ little from questions a child asks of a new friend: Where do you come from? How old are you? Such musings first spawned legends in which heroes used supernatural powers to mold the planets and sculpt the landscape. Eventually, researchers began to apply scientific principles to **cosmology**, the study of the overall structure and history of the Universe, and a different picture has emerged.

In this chapter, we begin with a brief introduction to the principles of scientific cosmology. We explain the basic architecture of the Universe, introduce the Big Bang theory for the formation of the Universe, and discuss the nebular theory for the birth of the Solar System. Finally, we characterize our home planet by building an image of its surroundings, surface, and interior. This introductory high-speed tour of the Earth provides a context for the remainder of this book.



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

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)

1.2 An Image of Our Universe

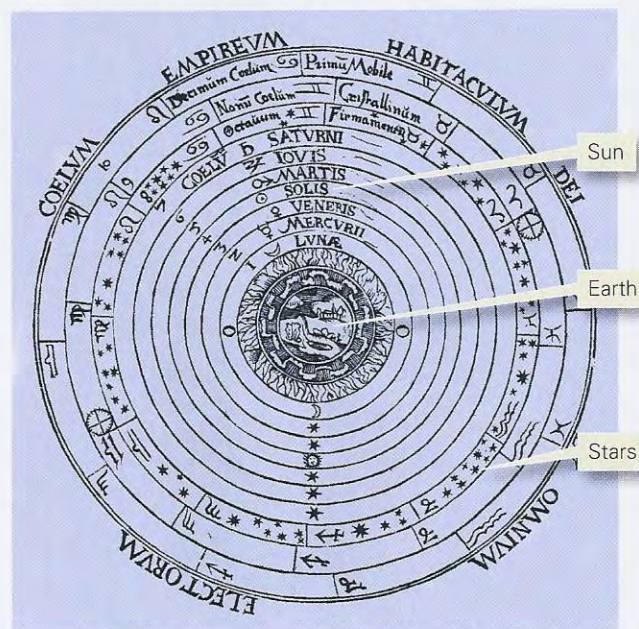
Stars, Galaxies, and Beyond

Think about the mysterious spectacle of a clear night sky. What objects are up there? How far away are they? How do they move? How are they arranged? In addressing such questions, ancient philosophers learned to distinguish *stars* (points of light whose locations are fixed, relative to each other) from *planets* (tiny spots of light that move relative to the backdrop of stars). Over the centuries, two schools of thought developed concerning how to explain the configuration of stars and planets, and their relationships to the Earth, Sun, and Moon. The first school advocated a **geocentric model** (Fig. 1.1a), in which the Earth sits motionless at the center of the Universe while the Moon and the planets whirl around it, and everything lies inside a revolving globe of stars. The second school advocated a **heliocentric model** (Fig. 1.1b), in which the Sun lies at the center of the Universe while the Earth and other planets orbit around it.

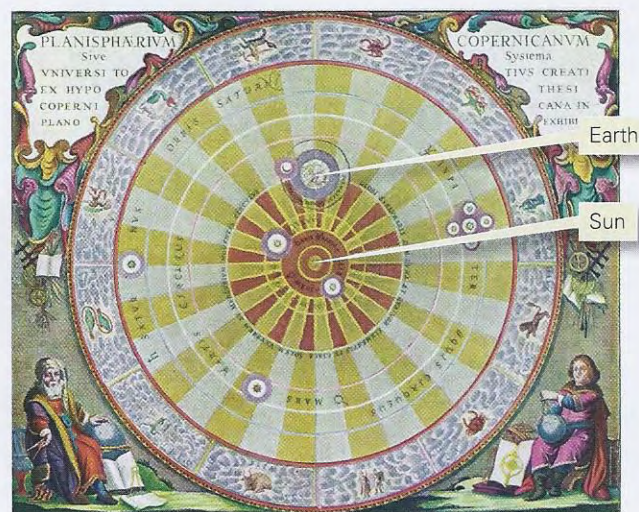
For millennia, the geocentric model garnered the most followers, due to the influence of an Egyptian mathematician, Ptolemy (100–170 C.E.), who developed equations that appeared to predict the wanderings of the planets in the context of the model, and thus seemed to prove the model. During the Middle Ages (ca. 476–1400 C.E.), church leaders in Europe adopted the geocentric model as dogma, because it justified the comforting thought that humanity's home occupies the most important place in the Universe, the center. 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 gradually came to realize that the Earth and planets did indeed orbit the Sun, so the Earth could not possibly sit at the center of the Universe, and that orbits are elliptical, not cylindrical. As the Renaissance progressed, Isaac Newton (1642–1727) established the foundations of physics and optics, and others began to understand fundamental phenomena of chemistry. In the light of this work, the language and laws of modern science

FIGURE 1.1 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.

came into focus. Using this language, we now define the **Universe** as all of space and the matter and energy within it. **Box 1.1** provides a brief refresher on the meanings of these terms, and a few related ones.

As telescopes and other instruments improved so that astronomers could see and measure features progressively farther into space, the interpretation of stars evolved. Although it looks like a point of light, a **star** is actually an

FIGURE 1.2 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.

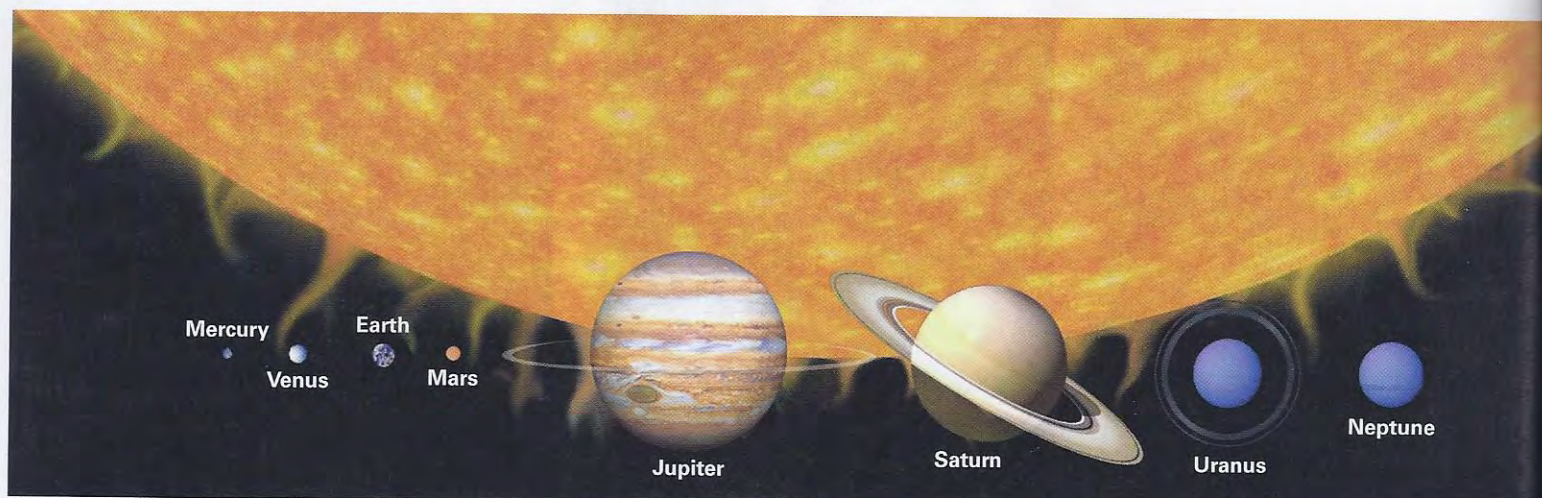
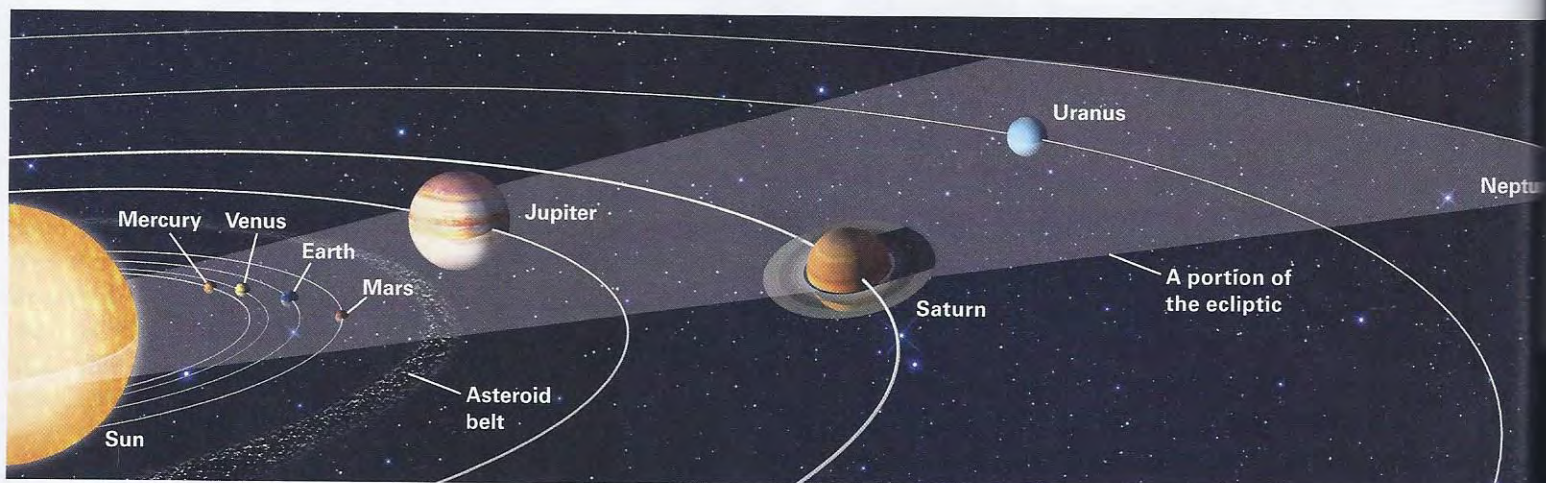
immense ball of plasma (incandescent gas) that emits intense heat and light. Stars are not randomly scattered through the Universe. Rather, gravity holds them together in immense groups called **galaxies**. Our Sun, together with over 300 billion other stars, makes up the *Milky Way galaxy*. From our vantage point on Earth, the Milky Way looks like a hazy band (Fig. 1.2a), but if we could view the Milky Way from a great distance, it would resemble a flattened spiral with great curving arms slowly swirling around a glowing, disk-like center (Fig. 1.2b). Presently, our Sun lies near the outer edge of one of these arms, orbiting the center of the Milky Way once every 250 million years. Astronomers estimate that more than 100 billion galaxies constitute the visible Universe (Fig. 1.2c). Clearly, human understanding of Earth’s place in the Universe has evolved radically over the past few centuries. Today, we realize that neither the Earth, nor the Sun, nor even the Milky Way occupies the center of the Universe—and everything is in motion.

Welcome to the Neighborhood: Our Solar System

Our Sun’s gravitational pull holds on to many objects which, together with the Sun, comprise the **Solar System** (Fig. 1.3a). 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—first photographed close up in 2015—does not fit the modern definition of a planet because it has not cleared its orbit of other objects, so it has been dropped from the roster. The eight planets orbit the Sun in the same direction and more or less in the same plane, called the **ecliptic** (Fig. 1.3b). Our Solar System is not alone in hosting planets. Land-based instruments, as well as those of the Kepler Space Telescope, have allowed astronomers as of 2015 to locate over 2,000 *exoplanets*, planets that orbit stars other than our Sun. Some of these are similar in size to the Earth.

Planets in our Solar System differ radically from one another in both size and composition. The inner planets (Mercury, Venus, Earth, and Mars), the ones closer to the Sun, are relatively small. These are called 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

FIGURE 1.3 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 were 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.

System. The overall composition of giant planets differs markedly from that of terrestrial planets. Specifically, 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*. While Neptune and Uranus do contain significant quantities of hydrogen and helium, they also contain solid water, ammonia (NH_3), and methane, so these planets are known as the *ice giants*. Note that researchers use 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.

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 1, Mars has 2, and Jupiter has at least 67. Some moons, such as the 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 100 m 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. Most of these icy bodies are tiny, but a few (including Pluto) are spheres with diameters of over 1,500 km and are known as *dwarf planets*. 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 heat up and release long tails of gas and dust—these objects are **comets**.

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 How do the inner planets differ from the outer planets?

1.3 Forming the Universe

A Key Clue: Discovering That the Universe Expands

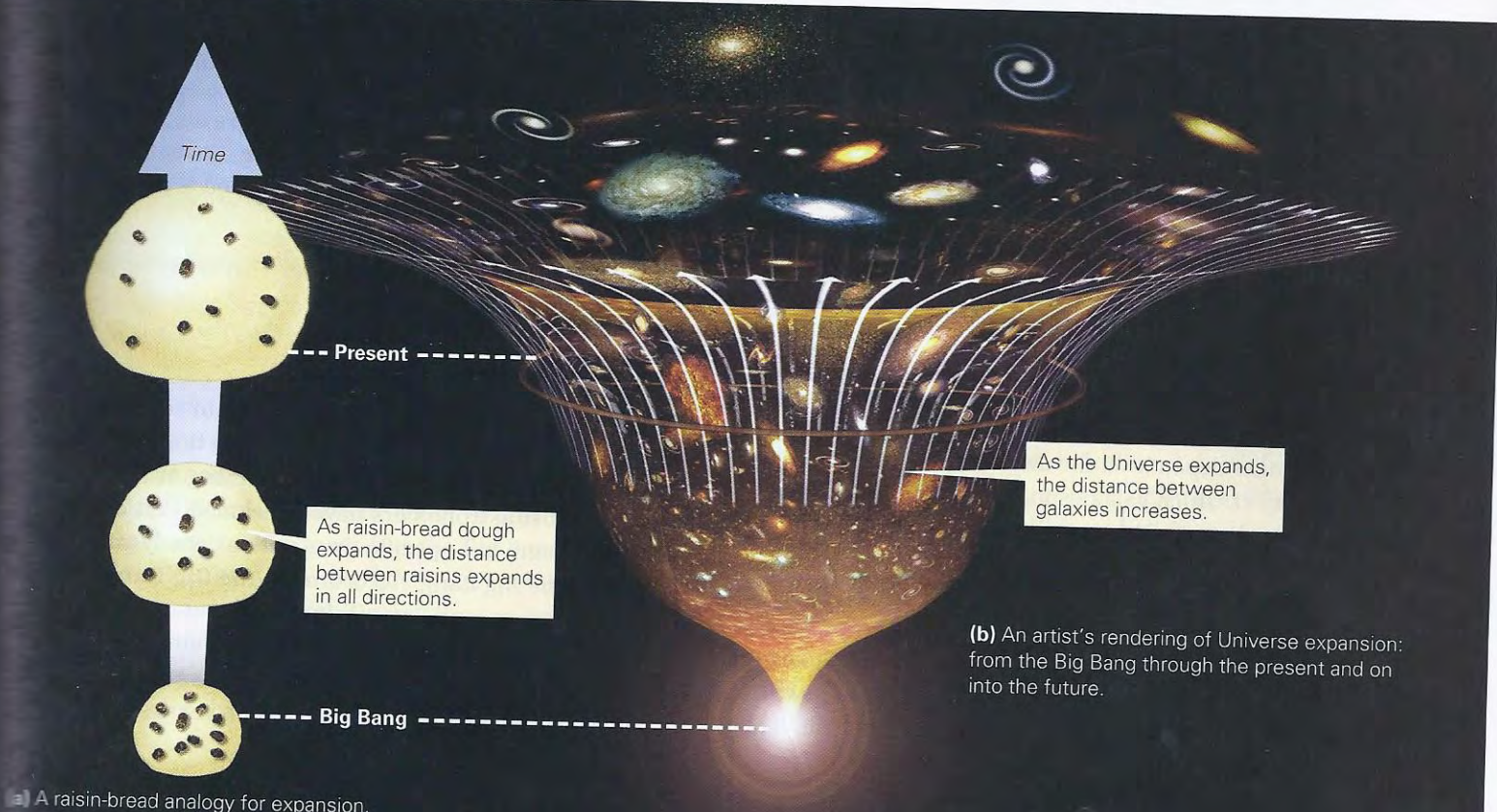
We stand on a planet, in orbit around a star, speeding through space on the arm of a galaxy. Beyond our galaxy lie hundreds of billions of other galaxies. Where did all this “stuff”—the matter of the Universe—come from, and when did it first form? For most of human history, a scientific solution to these questions seemed intractable. But in the 1920s, unexpected observations opened a new door of understanding. Astronomers such as Edwin Hubble (1889-1953), 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 documented only the location and shape of newly discovered galaxies, but eventually they also began to document the motion of the galaxies, which they could deduce by studying characteristics of the light emitted by the galaxies. (An astronomy book can provide the details of the method.) The results yielded a surprise that would forever change humanity's perception of the Universe. They found that all distant galaxies are moving away from the Earth, no matter which direction they looked. Furthermore, the farther away the galaxy lies, the faster it's moving away.

*Did you ever wonder...
if galaxies move?*

Around 1929, Hubble finally recognized what these observations meant—the volume of the whole Universe must be increasing! 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. 1.4a**). Note how raisins that were farther apart to start with have moved more, relative to each other, than raisins that were closer together to

FIGURE 1.4 The concept of the expanding Universe and the Big Bang.



BOX 1.1 Consider This...

The Basics of Matter, Force, and Energy

Matter, Atoms, and Molecules

The material substance of the Universe consists of *matter*—it takes up space and you can feel it. We refer to the amount of matter in an object as its *mass*, so an object with greater mass contains more matter. *Density* refers to the amount of mass occupying a given volume of space—a cubic centimeter of a denser material contains more mass than does a cubic centimeter of a less dense material.

An *element* is matter that cannot be subdivided into other components with different properties. If you were to keep subdividing an element into smaller and smaller pieces that have the same properties, you would end up with an *atom*, the smallest piece of an element that has the properties of the element. To picture how tiny atoms are, keep in mind that about 5 to 10 trillion atoms fit within the area of the period at the end of this sentence. We refer to elements by abbreviations, called *chemical symbols*, such as H (hydrogen), O (oxygen), Si (silicon), and Fe (iron).

Atoms themselves can be subdivided. Specifically, a single atom can contain three types of *subatomic particles*: *protons* that have a positive charge, *neutrons* that have a neutral charge, and *electrons* that have a negative charge. (Simplistically, the term “charge” refers to the electrical behavior of

the particle.) Protons and neutrons, which are about the same size, stick together in a dense ball, the *nucleus*, at the center of an atom—the “glue” that holds particles together in a nucleus is called a *nuclear bond*. Electrons are much smaller than protons or neutrons, and swirl around the nucleus in an *electron cloud*—it’s the outer edge of the electron cloud that defines the surface of an atom (Fig. Bx1.1a).

An atom of one element differs from an atom of another in terms of the number of protons in its nucleus. We specify this quantity as the *atomic number* of the element. Hydrogen atoms have an atomic number of 1, helium has an atomic number of 2, and iron has an atomic number of 26. With the exception of the most common form of hydrogen, all nuclei contain neutrons. The sum of the number of protons plus the number of neutrons roughly equals the *atomic mass* of an atom. All atoms, except for hydrogen, have neutrons, so for all atoms except hydrogen, the atomic mass is more than the atomic number.

Atoms tend not to exist in isolation, but rather attach to other atoms, connected by an invisible “glue” called a *chemical bond*. Scientists use the word *molecule* for a particle composed of a combination of two or more atoms bonded together. Some molecules contain atoms of only the

same element, whereas others contain atoms of two or more different elements. A substance in which molecules consist of two or more elements is a *compound*. We can specify the composition of a molecule by providing its *chemical formula*, a recipe which uses symbols to represent names and proportions of elements in a compound. For example, hydrogen gas consists of H_2 molecules, oxygen gas of O_2 molecules, water of H_2O molecules, and methane of CH_4 molecules. A molecule of methane contains one carbon atom and four hydrogen atoms. Note that a molecule is the smallest piece of a compound that has the characteristics of the compound, but not all molecules are pieces of compounds.

In everyday life, we see matter in four forms, called *states of matter* (Fig. Bx1.1b). In a *gas*, atoms and/or molecules are free to move with respect to one another, so a gas can expand to fill a volume that it occupies. In a *liquid*, atoms and/or molecules are loosely connected, so a liquid can flow and assume the shape of its container, but it will not change its volume as it flows. In a *solid*, atoms and/or molecules are strongly connected, so a solid can retain its shape for a long time. Under very high temperatures, plasma, a fourth state of matter forms—*plasma* is a gas in which the electrons have been stripped from atoms.

start with. Therefore, the velocity at which raisins move relative to each other depends on the distance between them, just as the velocity at which galaxies move away from each other depends on the distance between them.

The Big Bang

Hubble’s idea marked 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 beginning of the physical Universe. 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. The point “exploded” and the Universe began, according to current estimates, about 13.8 billion years ago (Ga).

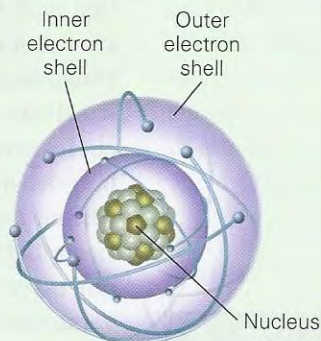
Force and Energy

Matter in the Universe does not sit still. Objects spin, they move from one place to another, and they pull on or push against each other. Isaac Newton showed that one mass can exert a *force* on another mass, and by doing so, change the velocity (speed and/or direction) of the mass. A change in velocity is called an *acceleration*, so Newton wrote this relationship as a scientific law: $F = ma$. In this equation, F is force, m is mass, and a is acceleration.

Forces can be applied in two ways. A *contact force* happens when one mass touches another—for example, you apply a contact force when you strike a ball with a bat and send the ball careening away. A *field force* happens when an object applies a force to another object without touching it. Examples of field forces include *gravity*, which is the attraction that one mass exerts on another, and *magnetism*, which is the attraction or repulsion that a magnet or electric current exerts on magnetic or electrically charged materials.

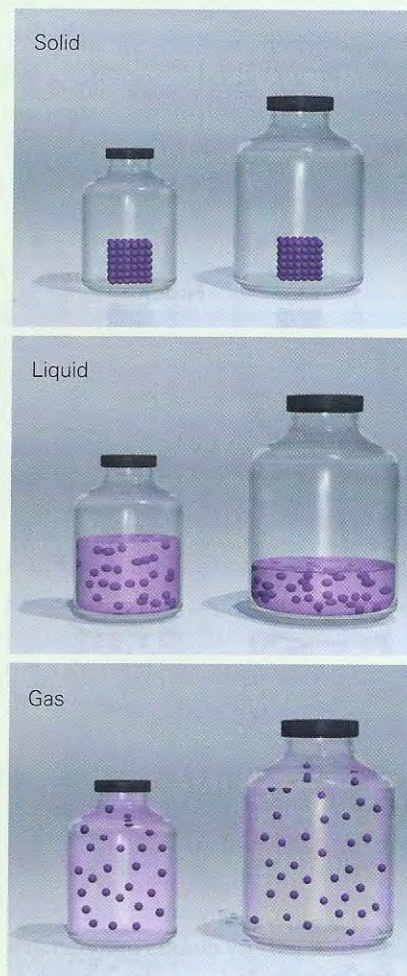
Simplistically, *work*, in the jargon of physics, is the consequence of a force acting on an object over a distance. For example, when you lift a weight by 1 meter, against the pull of gravity, you have done work. If you lift the same weight by 2 meters, you have done twice as much work. You also do work when you heat a pot of water and the water turns to steam that rises into the air. In other words, work happens when a mass has changed its position or state.

FIGURE Bx1.1 The nature of atoms and matter.



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

Physicists refer to the ability or capacity of a system (a specified region of space, of any size, and all it contains) to do work as energy. A moving object, light, magnetism, and gravity all can cause matter to change in some way, and thus can do work, so they provide energy. We can distinguish between *kinetic energy*, the energy of motion, and *potential energy*, the energy stored in a mass. A flying ball has kinetic energy, which can do work when it strikes a window and shatters the glass. A boulder sitting on a hillslope has potential energy, because gravitational force is pulling on it, so it could move (bounce downhill), if the dirt beneath it gives way. Similarly, a liter of gasoline contains potential energy, in that if it burns, it can cause a car to move.

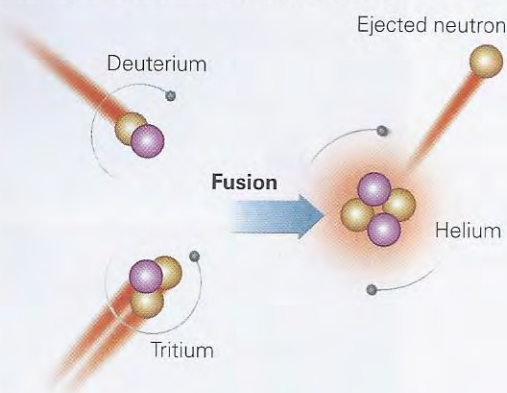


(b) The three common states of matter. Solids keep their shape, liquids conform to the shape of their container without changing density, and gases expand to fill their container.

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 Big Bang (**Fig. 1.4b**). According to this model, profound change happened at a fast and furious rate at the outset. During the first instant of existence, the Universe was so small, so dense, and so hot that it consisted entirely of energy—atoms, or even the smallest subatomic particles that make up atoms (see Box 1.1), could not

even exist. Within a few seconds, however, subatomic particles (neutrons, protons, and electrons) came into existence. And by the time the Universe reached an age of 20 minutes, all hydrogen atoms that would form had formed (including normal hydrogen, which consists only of a proton, and two other versions that include neutrons), and enough hydrogen atoms had joined together to form helium atoms so that the proportion of hydrogen to helium in the newborn Universe was about 3 to 1. The process by which the nuclei of two smaller atoms collide, stick together, and form a new atom with a larger

FIGURE 1.5 Fusion happens when colliding particles fuse to form a new, larger nucleus. Deuterium and tritium are versions of hydrogen in which a proton fused to one or two neutrons, respectively. These nuclei, in turn, can collide to form a helium nucleus.



nucleus is called **nuclear fusion** (Fig. 1.5). Formation of new nuclei during and immediately after the Big Bang is called *Big Bang nucleosynthesis* because it happened before any stars existed. This process could produce only small atoms, that is, atoms with a small number of protons (atomic number less than 5).

Eventually, the Universe became cool enough for chemical bonds to bind atoms of certain elements together to produce molecules (see Box 1.1). Most notably, hydrogen atoms joined to form molecules of H_2 . As the Universe continued to expand and cool further, atoms and molecules slowed down and accumulated into patchy clouds of hydrogen and helium gas called **nebulae** (see chapter opening photo).

Birth of the First Stars: The Nebular Theory, Part 1

When the Universe reached its 200 millionth birthday, it contained immense, slowly swirling nebulae of hydrogen and helium gas separated by vast voids of empty space. Empty space is a **vacuum**, a region in which the density of matter is extremely low. In the regions between nebulae, the vacuum of space may contain less than 1 atom or molecule per cubic meter—by comparison, the air you breathe at sea level contains on the order of 300,000,000,000,000,000,000

molecules per cubic meter. 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 attraction—a type of force—on its surroundings (see Box 1.1). As Isaac Newton first pointed out, the amount of attraction depends on the amount of mass (the larger the mass, the greater its attraction) and on the distance between the masses (gravitational force increases as objects get closer to each other). Somewhere in the young Universe, gravity produced by 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. As progressively more gas drew into this denser region, the dense region became even denser, 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 bulbous plate-like shape called an **accretionary disk** (Fig. 1.6). Eventually, gravity caused the inner portion of the accretionary disk to collapse inward to form a dense ball. When gas in this ball squeezed into a smaller and smaller space, the gas's temperature increased dramatically (Box 1.2), so the ball became hot enough to glow. At this time, it became a **protostar**. The remaining mass of the accretionary disk, as we will see, eventually clumped into smaller spheres, the planets. The overall model for explaining the sequence of stages during which stars and planets form from a nebula is called the **nebular theory**.

A protostar continues to grow, by pulling in successively more mass, until its core becomes so dense, and its temperature so high (about 10,000,000°C), that hydrogen nuclei within it move incredibly fast and slam together so forcefully that fusion takes place and new helium nuclei form. Fusion reactions produce huge amounts of energy, so when they begin, the protostar “ignites” to become a nuclear furnace, and the ball becomes a true star. The first true star may have formed about 800 million years after the Big Bang, and when this happened, the first starlight pierced the newborn Universe. Star formation happened again and again in the young

FIGURE 1.6 Nebular theory for planet formation.



Universe, and soon many first-generation stars had come into existence.

First-generation stars tended to be very massive, having 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 runs out of fuel, collapses, explodes, and becomes a **supernova**. This name comes from the impression, when their light reaches the Earth, that a new but temporary star has appeared in the night sky. The giant explosion blasts much of the star's matter back into space. Thus, not long after the first generation of stars formed, the Universe began to be peppered with the first generation of supernovas.

TAKE-HOME MESSAGE

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 about 13.8 Ga. According to the nebular theory, 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 What elements made up most of the nebulae in the very young Universe?

1.4 Forming the Solar System, Including the Earth

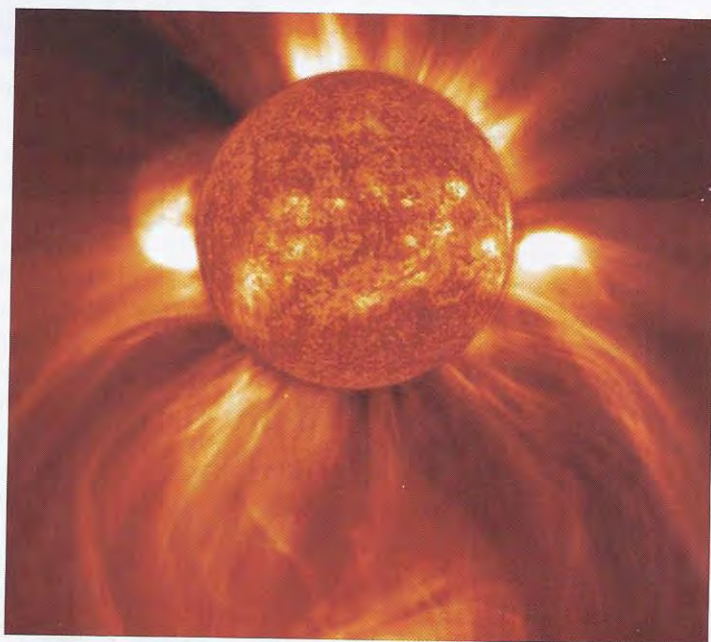
We Are All Made of Stardust

Nebulae from which the first-generation stars formed consisted entirely of the lightest atoms (atoms with a very small nucleus), because only these 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 heavier elements with larger atomic numbers (such as carbon, sulfur, silicon, iron, gold, and uranium) form? Physicists have shown that intermediate-weight elements form by fusion reactions during the life cycle of stars, a process called **stellar nucleosynthesis**. Because of stellar nucleosynthesis, we can consider stars to be “element factories,” constantly fashioning larger atoms out of smaller atoms. Most heavy atoms, those with atomic numbers greater than that of iron, require even hotter environments to form than generally occurs within a star. In fact, most very heavy atoms form during the

inconceivably hot conditions of supernova explosion, a process called **supernova nucleosynthesis**.

How do the atoms formed in stars get into space? Some escape 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. 1.7a). Some escape only when a star dies. Large

FIGURE 1.7 Element factories in space.



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



(b) This expanding cloud of gas, ejected into space from a supernova explosion whose light reached the Earth in 1054 c.e., is called the Crab Nebula.

Heat, Temperature, and Heat Transfer

The atoms and molecules that make up an object do not stay rigidly fixed in place, but rather jiggle and jostle with respect to one another. This movement creates *thermal energy*—the faster the atoms move, the greater the thermal energy and the “hotter” the object. Put another way, the thermal energy in a substance represents the sum of the kinetic energy (energy of motion) of all the substance’s atoms in a given volume. This includes the back-and-forth displacements that an atom makes as it vibrates, as well as the movement of an atom from one place to another. Because of the relation between kinetic energy and thermal energy, kinetic energy can be transformed into thermal energy. You can demonstrate this with a simple home experiment. Start to hammer a large nail into a block of hardwood, and then after a few strong blows, touch the end of the nail. You’ll feel that it has gotten warmer. The reason is that although some of the kinetic energy of the moving hammer head has gone into pushing the nail into the wood, most has gone into agitating the atoms in the nail. Because the atoms have started moving around more quickly, the thermal energy in the nail has increased.

When we say that one object is hotter or colder than another, we are describing its temperature. **Temperature** is a measure of warmth relative to a known reference value, and represents the average kinetic energy of atoms in the material. When we compress a gas, the molecules collide more frequently and so the average kinetic energy in the gas increases, so the temperature goes up. To specify temperature, meaning to indicate relative hotness or coldness, scientists use the *centigrade*, or Celsius, *scale*, whose unit is 1 degree (1°C). The scale is calibrated so that the boiling point of water at sea level is 100°C , and the freezing point is 0°C . An increment of 1°C , therefore, represents 1/100 of the temperature difference between the boiling and freezing points of water. (Note that the English system, commonly used in weather reports in the United States, uses the *Fahrenheit scale* for temperature. On this scale water boils at 212°F and freezes at 32°F .)

Heat is the thermal energy transferred from one object to another. We measure heat in *calories*. One thousand calories can heat 1 kilogram of water by 1°C . The transfer of heat from one place to another can occur in four distinct ways:

- **Radiation:** When an object glows, it sends electromagnetic waves (such as visible light, infrared light, and ultraviolet light) into the space around it. This energy, called *radiation*, can cause an object at a distance from the source to heat up, even if there is a vacuum between the source and the object. Radiation traveling from the Sun is responsible for heating the Earth’s surface (Fig. Bx1.2a).
- **Conduction:** If you stick the end of an iron bar in a fire, *conduction* takes place and heat moves up the bar. This happens because atoms in the bar at the hot end start to vibrate more energetically, and this motion incites atoms farther up the bar to start jiggling. Though heat flows along the bar, the atoms do not actually move from one locality to another (Fig. Bx1.2b). Heat always conducts from hotter to cooler material.
- **Convection:** When you place a pot on a stove and heat it, water at the base of the pot gets hotter and expands, so its density decreases. The hot, less-dense water becomes buoyant relative to the colder, denser water above it. In a gravitational field, buoyant material rises if

stars, as we’ve noted, blast an immense amount of matter into space during supernova explosions (Fig. 1.7b). Small or medium-sized stars (like our Sun) do not explode, but rather balloon to become a *red giant*, when they start to run out of fuel. Eventually, when the star runs out of fuel entirely, its interior collapses, leaving its outer shells of gas to drift out into space. Once ejected into space, atoms from stars, collapsed red giants, and supernova explosions form new nebulae or mix back into existing nebulae.

When the first generation of stars died, they left a legacy of new, heavier elements that mixed with residual hydrogen and helium 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 progressively greater proportion of heavier elements. Because not all stars live for the same duration of time, at any given moment the Universe contains multiple generations of stars. Our Sun may be a second- or third-generation star, so 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 atoms that make up your body once resided inside a star!

Did you ever wonder...
where the atoms in your
body first formed?

the material above it is weak enough to flow out of the way. Since liquid water flows easily, the hot water can rise. When this happens, cold water sinks to take its place (Fig. Bx1.2c). The resulting circulation, during which flow of the material itself carries heat, is called *convection*; the path of flow defines *convection cells*.

Advection: When a hot fluid flows into cracks and pores within a solid, it heats up the solid. Transfer of heat carried by a hot fluid passing through a solid is called *advection*. The hotness of a metal water pipe's surface, for example, comes from the hot water in the pipe. Advection occurs in the Earth when molten rock rises into the crust (Fig. Bx1.2d).

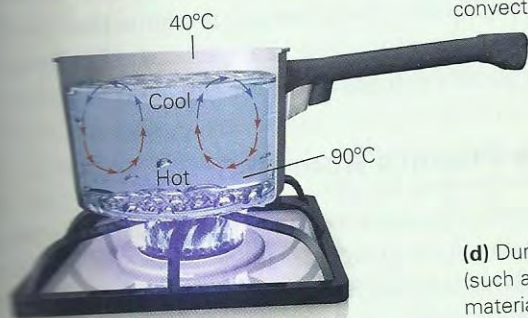
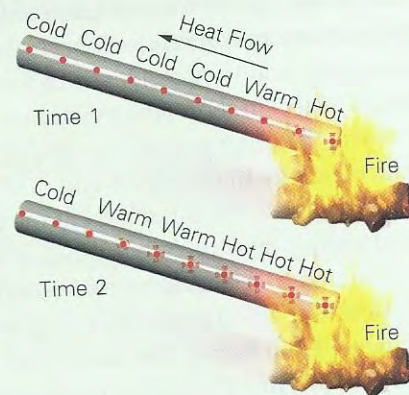


FIGURE Bx1.2 The four processes of heat transfer.



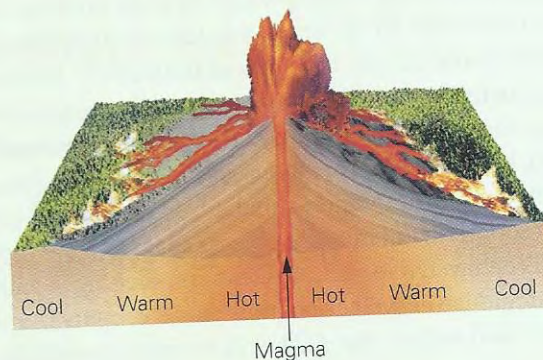
(a) Radiation from sunlight warms the Earth.



(b) Conduction occurs when you heat the end of an iron bar in a flame. Heat flows from the hot region toward the cold region as vibrating atoms cause their neighbors to vibrate.

(c) Convection takes place when moving fluid carries heat with it. Hot fluid rises while cool fluid sinks, setting up a convection cell.

(d) During advection, a hot liquid (such as molten rock) rises into cooler material, and heat then conducts from the hot liquid into the cooler material.



Forming the Solar System: The Nebular Theory, Part 2

Earlier in this chapter, we introduced the nebular theory as a scientific concept that explains how stars form from nebulae. But we delayed our discussion of how the planets and other objects in our Solar System originated until we had discussed the production of heavier atoms such as carbon, silicon, iron, and uranium, because terrestrial planets consist predominantly of these elements. Now that we've discussed stars as element factories, we return to the early history of the Solar System and extend the nebular theory to explain how planets, moons, asteroids, and comets form. According to the nebular

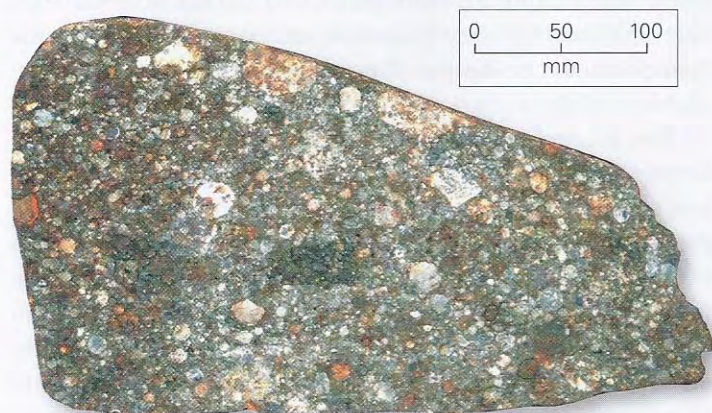
theory, these objects came from matter in the flattened outer part of the accretionary disk, the material that did not become incorporated into the star. This outer part is called the *protoplanetary disk*.

The protoplanetary disk from which our Solar System formed contained all 92 elements, some as isolated atoms and some bonded to others in molecules. Geologists divide the material formed from these atoms and molecules into two classes. **Volatile materials**—such as hydrogen, helium, methane, ammonia, water, and carbon dioxide (CO_2)—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*, some volatiles can freeze into ice. (Recall that we do not limit use of the word *ice* to solid water alone.) **Refractory materials** are those that melt only at high temperatures, and they condense to form solid soot-sized particles of “dust” in the coldness of space. As the proto-Sun began to form, the inner part of the disk became hotter, causing volatile elements to evaporate and drift to the outer portions of the disk. Thus, the inner part of the disk ended up consisting predominantly of refractory dust, whereas the outer portions accumulated large quantities of volatile materials and ice.

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 and electrical attraction, forming a series of concentric rings around the proto-Sun. In these rings, matter was denser, and particles got close enough to each other to attract. First, soot-sized particles merged to form sand- to marble-sized grains. These then 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** (Fig. 1.8), bodies whose diameter exceeded about 1 km. Because of their mass, the planetesimals exerted enough gravitational attraction to pull in other objects that were nearby. Planetesimals behaved 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. Eventually, victors in the competition to attract mass grew into **protoplanets**, bodies approaching the size of today’s planets. Once a protoplanet succeeded in incorporating virtually all the debris within its orbit, it became a full-fledged planet.

FIGURE 1.8 The grainy texture of this meteorite fragment may resemble the texture of a small planetesimal.



Early stages in the planet-forming process probably occurred very quickly—some computer models suggest that it may have taken less than a million years to go from the dust and gas stage to the large planetesimal stage. Planets may have grown from planetesimals in 10 to 200 million years. In the inner orbits, where the protoplanetary disk consisted mostly of refractory dust, small terrestrial planets (such as the Earth) composed of rock and metal formed, whereas in the outer part of the Solar System, where significant amounts of volatiles remained, the rocky and metallic protoplanets became surrounded by thick shells of gas and/or ice, and evolved into the giant planets. Fragments of materials that were not incorporated in planets remain today as asteroids and comets.

When did the Solar System form? Using techniques introduced in Chapter 10, geologists have found that special types of meteorites thought to be leftover planetesimals formed at 4.57 Ga, and thus consider that date to be the birth date of the Solar System. If the 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.

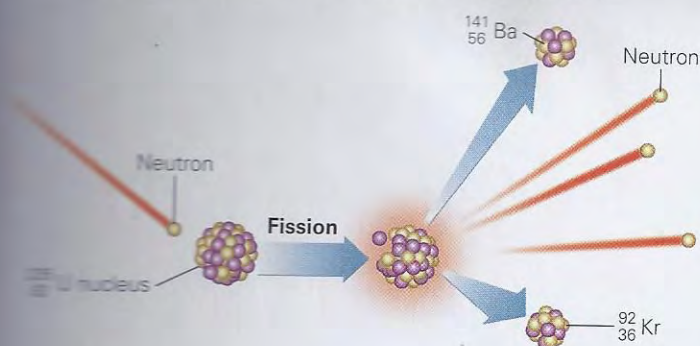
Why Are Planets Round?

Small planetesimals were jagged or irregular in shape, and asteroids today have irregular shapes. Planets and larger moons, on the other hand, are more or less spherical. Why? The rock composing a small planetesimal is cool and strong enough so that the force of gravity cannot cause the rock inside the object to flow, so irregularities like bumps and dimples can survive. But once a planetesimal grows beyond a certain critical size (about 500 km in diameter), its interior becomes warm and soft enough to flow in response to the pull of gravity. As a consequence, protrusions are pulled inward toward the center, and the planetesimal takes on a special shape—a sphere—for in a sphere, mass is evenly distributed around the center so the force of gravity can be nearly the same at all points on its surface (*Geology at a Glance*, pp. 24–25).

Differentiation of the Earth

When planetesimals started to form, 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 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

FIGURE 1.9 During nuclear fission, a uranium atom splits to form two smaller atoms. The process releases neutrons.



matter is squeezed into a smaller volume (see Box 1.2), and the heat produced from the decay of radioactive elements. A *radioactive element* is one whose nuclei spontaneously emits subatomic particles, or undergoes **nuclear fission** by breaking into two smaller nuclei (Fig. 1.9). Such "decay" breaks nuclear bonds and releases energy. In bodies whose temperature rose sufficiently to cause internal melting, denser iron alloy separated out and sank to the center of the body, whereas lighter rocky materials remained in a shell surrounding the center (Fig. 1.10). By this process, called **differentiation**, protoplanets and large planetesimals developed internal layering early in their history. As we will see later in this chapter, the Earth's central ball of iron alloy constitutes the body's *core* and the shell surrounding it is its *mantle*. Geologists have concluded that differentiation of protoplanets had occurred by

4.54 Ga, based on the ages of meteorites that represent fragments of differentiated protoplanets that later broke apart, and they consider this age to be the age of the Earth.

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. When they became large enough, planets differentiated, with denser materials sinking to the center.

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

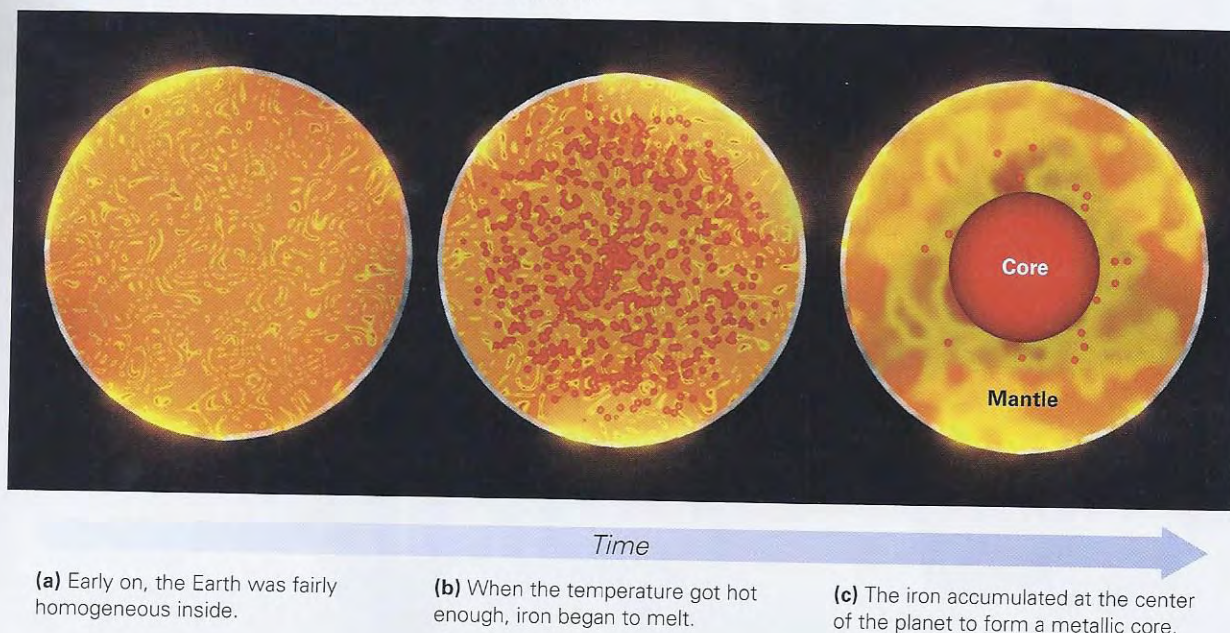
1.5 Earth's Moon and Magnetic Field

The Earth does not orbit the Sun all on its own. Rather, the near space around the Earth encompasses two important entities—the Moon and the magnetic field.

The Moon and Its Formation

As seen from Earth, the Moon glows an eerie white. Its radius of 1,737 km is about a quarter of the Earth's. Even with the

FIGURE 1.10 Differentiation of the Earth's interior.



**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.

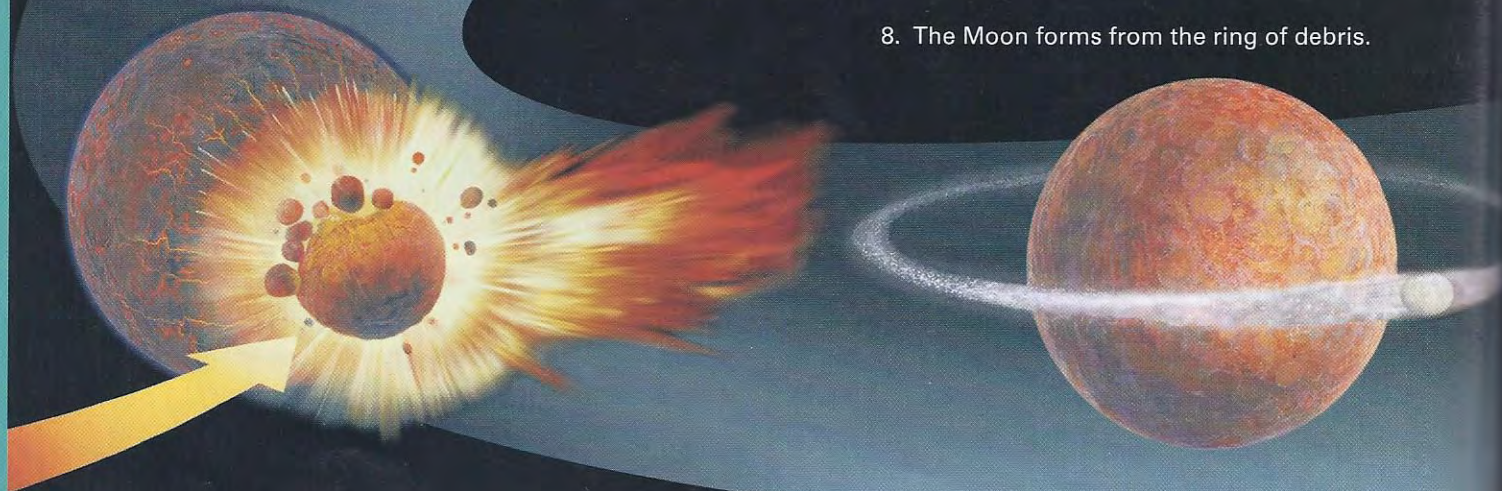
2. Gravity pulls gas and dust inward to form an accretionary disk. Eventually a glowing ball—the proto-Sun—forms at the center of the disk.

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

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.

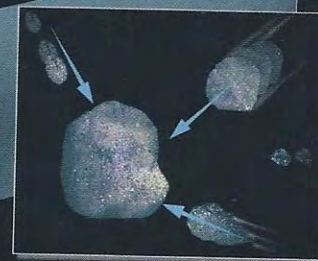
7. Soon after the Earth forms, a protoplanet collides with it, blasting debris that forms a ring around the Earth.

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.



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

naked eye, you can see that its surface is variable in character—the whiter areas, the lunar highlands, have been pockmarked by countless craters, whereas the darker areas, the maria (singular: mare), are smoother and less cratered (**Fig. 1.11**). Gravitational interaction between the Earth and the Moon keeps the same side of the Moon facing the Earth, so humans did not know what the far side of the Moon looked like until satellites and astronauts sent back pictures.

How did the Moon form? The answer remains a subject of scientific debate. In the currently most popular hypothe-

Did you ever wonder...

if the Moon is as old as the Earth?

sis, the Moon resulted when a protoplanet, perhaps comparable in size to Mars, collided with the newborn Earth. In the process, the colliding body disintegrated and melted or

even vaporized, along with a large part of the Earth's mantle (see *Geology at a Glance*, pp. 24–25). A ring of debris formed around the remaining, probably molten Earth. Gravity quickly caused this material to coalesce into the Moon. Not all moons in the Solar System necessarily formed in this manner. Some may have been independent protoplanets or comets

FIGURE 1.11 The Earth's moon has distinct maria (dark areas), and lighter-colored, intensively cratered highlands.



that were captured by a larger planet's gravity. Based on analysis and the dating of Moon rocks, most geologists have concluded that the Moon-forming event happened at about 4.53 Ga. Most of the craters on the Moon formed between the time of the Moon's birth and about 3.0 Ga. In fact, around 3.9 Ga, heavy bombardment by meteorites may have pulverized the surfaces of planets. The Earth must have been hit as frequently as the Moon, but on the Earth, geologic processes have erased most of these craters.

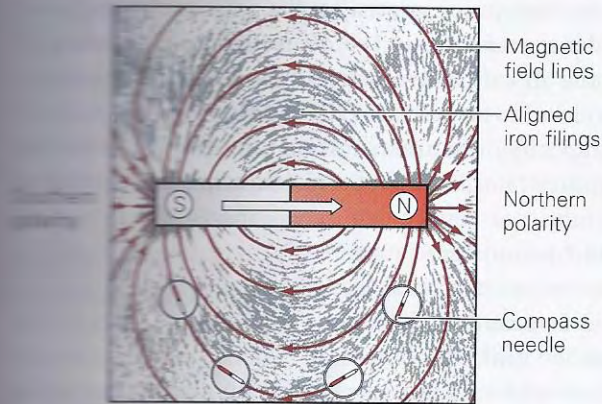
Earth's Magnetic Field

A **magnetic field**, in a general sense, is the region affected by the force emanating from a magnet. Magnetic force, which grows progressively stronger as you approach the magnet, can attract or repel another magnet and can cause charged particles to move. Earth has a magnetic field, which is largely a **dipole**, meaning that it has two different ends—a north pole and a south pole—just like the magnetic field around a familiar bar magnet (**Fig. 1.12a, b**). When you bring two bar magnets close to one another, their opposite poles attract and their like poles repel. By convention, we represent the orientation of a magnetic dipole by an arrow that points from the south pole to the north pole, and we represent the magnetic field of a magnet by a set of invisible magnetic field lines that curve through the space around the magnet and enter the magnet at its poles. Arrowheads along these lines point in a direction to complete a loop. Magnetized needles, such as iron filings or compass needles, when placed in a field, align with the magnetic field lines.

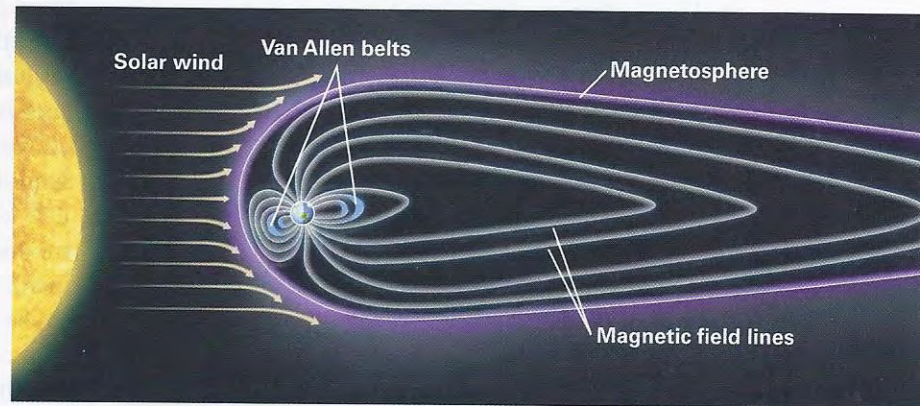
If we represent the Earth's magnetic field as emanating from an imaginary bar magnet in the planet's interior, the north pole of this bar lies near the south geographic pole of the Earth, whereas the south pole of the bar lies near the north geographic pole. (The *geographic poles* are the places where the spin axis of the Earth intersects the planet's surface.) Nevertheless, by convention geologists and geographers refer to the magnetic pole closer to the north geographic pole as the *north magnetic pole*, and the magnetic pole closer to the south geographic pole is called the *south magnetic pole*. By using this convention, the north-seeking end of a compass points toward the north geographic pole, since opposite ends of a magnet attract.

The Sun's stellar wind, known as the *solar wind*, interacts with Earth's magnetic field, distorting it into a huge teardrop pointing away from the Sun. The solar wind consists of dangerous, high-velocity charged particles. Fortunately, the magnetic field deflects most (but not all) of the particles, so that they do not reach Earth's surface. In this way, the magnetic field acts like a shield against the solar wind; the region inside this magnetic shield is called the **magnetosphere**.

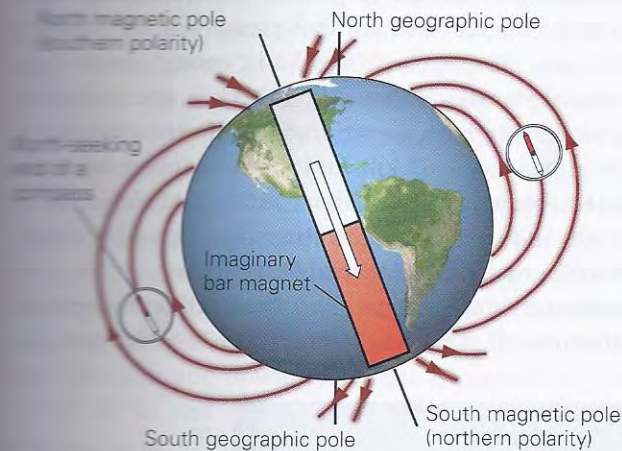
FIGURE 1.12 A magnetic field permeates the space around the Earth. It can be symbolized by a bar magnet.



(a) Magnetic field lines produced by a bar magnet point into the magnet's south pole and out from its north pole.



(c) Earth behaves like a magnetic dipole, but the field lines are distorted by the solar wind. The Van Allen radiation belts trap charged particles.



(b) We can represent the Earth's magnetic field by an imaginary bar magnet inside.

(Fig. 1.12c). At distances of about 3,000 km and 10,500 km out from the Earth, the *Van Allen radiation belts*, named for American physicist, who first recognized them in 1959, have developed. These belts, which lie well within the magnetosphere, trap solar wind particles as well as cosmic rays (nuclei of atoms emitted from supernova explosions) that were moving so fast they were able to penetrate the weaker outer part of the magnetic field. Some charged particles make it past the Van Allen belts and are channeled along magnetic field lines to the polar regions of Earth.

TAKE-HOME MESSAGE

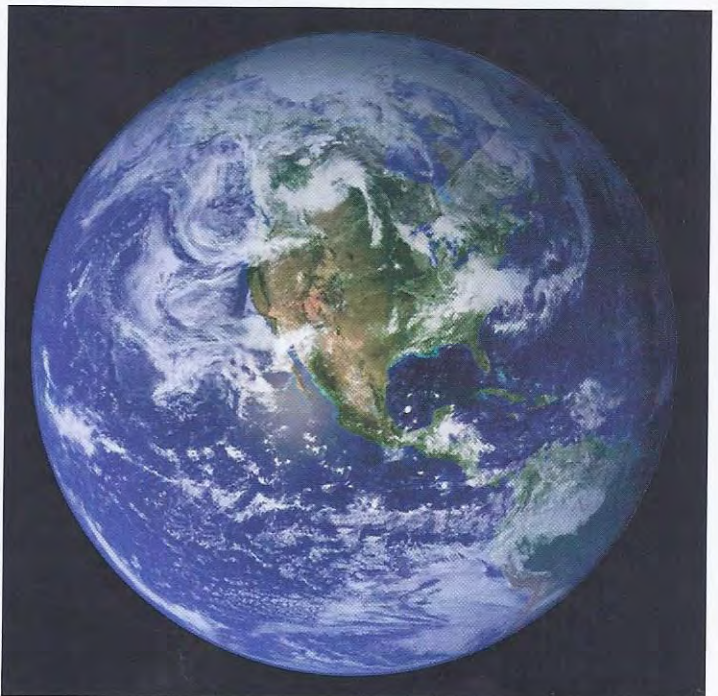
A collision of a protoplanet with the Earth soon after formation of the Earth may have yielded the material from which the Moon formed. The Earth produces a magnetic field that deflects solar wind.

QUICK QUESTION What is a magnetic pole?

1.6 Introducing the Earth System

So far in this chapter, we've described scientific ideas about how the Universe, and then the Solar System, formed. Now let's focus on our home planet and develop an image of the Earth's overall architecture. To develop this image, pretend that we are explorers from space rocketing toward the Earth for a first visit. As our spacecraft approaches the Earth, we admire its beautiful bluish glow (Fig. 1.13). At an elevation of about 10,000 km

FIGURE 1.13 The Earth, as seen from space, has an overall bluish glow. You can distinguish land, sea, clouds, ice, and vegetation.



(6,200 miles) above the surface, we slow the spacecraft and go into orbit. The Earth almost fills our field of view, and we can see that its surface and surroundings consist of several distinct realms or domains, which we begin to explore. We'll see that all these realms interact with one another and exchange materials, over time. Geologists refer to all the realms, and the interactions among them, as the **Earth System**.

The Atmosphere

At an elevation of 10,000 km, our instruments detect a slight increase in the density of gas outside. This change marks the feather edge of the Earth's **atmosphere**, the envelope of gas

that surrounds the planet (**Fig. 1.14a**). The weight of overlying atmosphere pushes down on the atmosphere below, so both the density of air and the *air pressure* (the amount of push that the air exerts on material beneath it) increases progressively closer to the surface (**Fig. 1.14b**).

We can specify pressure in units of force per unit area. One such unit, an *atmosphere* (abbreviated atm), has a value of 1.03 kilograms per square centimeter (14.7 pounds per square inch), the average air pressure at sea level. In scientific discussions, another unit, the bar, is commonly used for defining pressure—an atmosphere and a bar are almost the same, for 1 atm = 1.01 bar. Air pressure (and therefore, density) decreases by half for every 5.6 km that you rise above sea level. Thus, at the peak of Mt. Everest, the highest point of the planet (8.85 km above sea level), air pressure is only 0.3 atm. People can't breathe in enough gas to survive for long at elevations above about 5.5 km. Because of the decrease in density with elevation, 99% of atmospheric gas lies at elevations below 50 km, and the atmosphere becomes barely detectable at elevations above 120 km. At elevations of between 700 and 10,000 km, the atmosphere gradually transitions into the vacuum of interplanetary space.

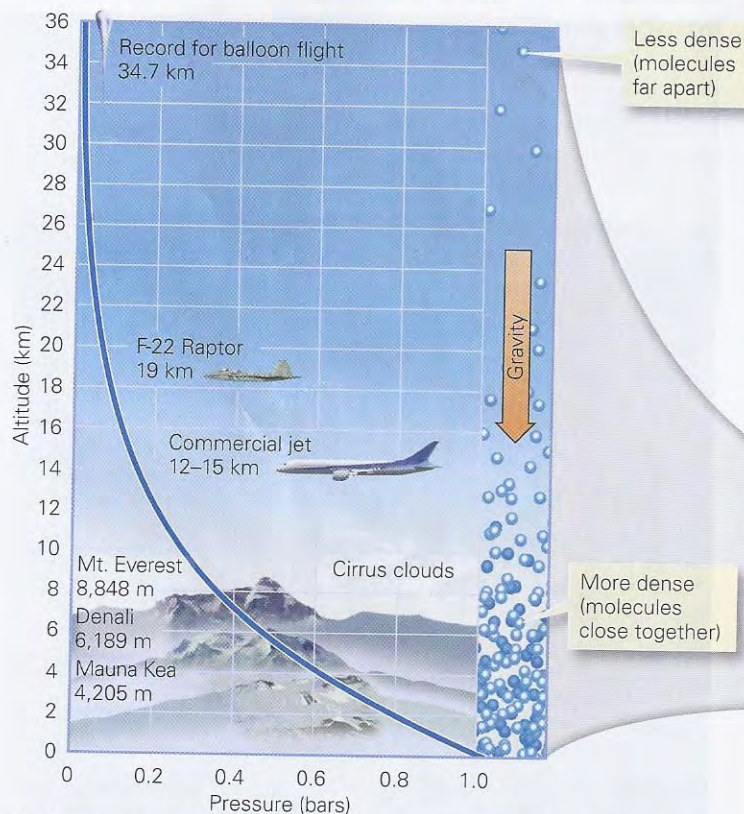
By analyzing samples of gas from the Earth's atmosphere, we find that overall, it currently consists of 78% nitrogen (N_2)

Did you ever wonder
how thick our atmosphere is

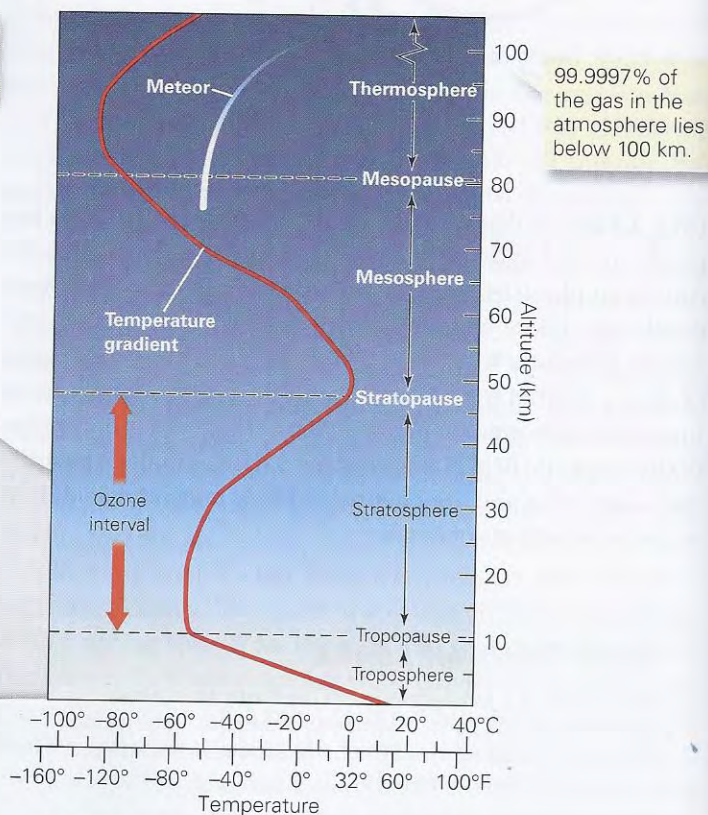
FIGURE 1.14 Characteristics of the atmosphere that envelops the Earth.



(a) An orbiting astronaut's photograph shows the haze of the atmosphere fading up into the blackness of space.



(b) Molecules pack together more tightly at the base of the atmosphere, so atmospheric pressure changes with elevation.



(c) The atmosphere can be divided into several distinct layers. We live in the troposphere.

and 21% oxygen (O_2). The remaining 1% consists of a variety of trace gases, including argon (Ar), carbon dioxide (CO_2), neon (Ne), methane (CH_4), ozone (O_3), carbon monoxide (CO), and sulfur dioxide (SO_2). We will see, in Chapter 19, that the composition of the atmosphere has evolved over time. Early in the Earth's history, the atmosphere consisted mostly of CO_2 and H_2O . Breathable quantities of O_2 have only existed since about the dawn of the Phanerozoic.

The temperature of the Earth's atmosphere changes with increasing distance from the Earth's surface, in some intervals getting hotter with increasing elevation and in some intervals getting cooler. Boundaries at which temperature stops decreasing and starts increasing, or vice versa, divide the atmosphere into layers. The layers of the atmosphere are named, in sequence from base to top: the *troposphere*, the *stratosphere*, the *mesosphere*, and the *thermosphere* (Fig. 1.14c). The term *exosphere* applies to the transition from air to space above 700 km. Boundaries between layers are named for the underlying layer. For example, the boundary between the troposphere and the overlying stratosphere is the *tropopause*.

As we circle the Earth, we can see the swirls and streaks of clouds, mists of tiny water droplets or hazes of tiny ice crystals, that float in the air (see Fig. 1.13). The complex distribution and shapes of clouds emphasize that the troposphere is in constant motion, with winds that transport air horizontally, and updrafts and downdrafts that transport air vertically. (Most winds and clouds develop only in the troposphere, where convection takes place rapidly; see Box 1.2 for a discussion of convection.) The distribution of clouds emphasizes that the water content of the atmosphere varies with location and over time. We also see that the atmosphere interacts with the magnetosphere. High-energy particles stream along the Earth's magnetic field lines toward the poles and interact with gases in the atmosphere (Fig. 1.15a). This causes the gases to glow, creating spectacular *aurorae*, pulsating sheets of color, in the atmosphere (Fig. 1.15b). Taking all of the characteristics of the Earth's atmosphere into account, we see that it is radically different in composition and density than the atmospheres of other terrestrial planets.

The Hydrosphere and Cryosphere

The surface of the Earth beneath the atmosphere presents a variety of different textures and colors. Our first task, as explorers, is to make a map of the planet. What features should go on this map? Starting with the most obvious, we note that water covers about 70% of the surface and land covers about 30% of the surface (see Fig. 1.13). About 98% of the water resides in the *oceans*, regions where the water contains about 3.5% dissolved salt and has an average depth of about 4.5 km. A relatively minor amount of water occurs as “fresh” (less

FIGURE 1.15 The aurorae are an atmospheric phenomenon.

(a) Charged particles flow toward Earth's magnetic poles.



(b) Particles cause gases in the atmosphere to glow, forming colorful aurorae in polar skies.

than 0.05% salt) surface water on land, in the form of lakes, streams, and swamps. A larger amount exists as **groundwater**, water filling tiny holes and cracks underground, down to a depth of several kilometers. Geologists refer to the realm including oceans, surface water on land, and groundwater as the **hydrosphere**.

In polar regions, and at high elevations where temperatures are colder, water occurs in solid form, as ice. Much of this ice has built into thick sheets or streams, called *glaciers*, that last all year and slowly flow in response to gravity. Ice also forms a relatively thin sheet over the surface of the ocean in polar regions, and near-surface groundwater remains frozen all year in the form of permanently frozen ground, or *permafrost*, adjacent to many glacier-covered areas. The frozen portion of the Earth's hydrosphere constitutes the **cryosphere**. The prefix *cryo-* comes from the Greek word *kryo*, meaning very cold or ice-like.

The Geosphere

The solid Earth, from the surface to the center, constitutes the **geosphere**. As we've seen, *land* refers to regions where the surface of the geosphere is exposed to the atmosphere. The *seafloor* refers to the surface portion submerged beneath the oceans. Today's Earth includes several large areas of land—called continents—and thousands of smaller ones—*islands*. As we'll see later in the book, the continents that we see today have not always existed. At times in the past, they were merged into vast supercontinents, or were divided into smaller pieces. Also, because sea level rises and falls over Earth history, some regions of what is currently dry land were

once submerged by shallow seas, and some regions that are now submerged were once dry. Similarly, since glaciers grow and shrink over Earth history, some areas of dry land today were covered by glaciers in the past.

The surface of the geosphere is not perfectly smooth (**Fig. 1.16**). From our spacecraft in orbit, we can see that the land surface elevation ranges from a few hundred meters below sea level (the shore of the Dead Sea) to 8.85 km above sea level (the peak of Mt. Everest). We call this variation **topography**. Our instruments also allow us to study **bathymetry**, variations in the depth of the seafloor. We find, along the edges of many continents, *continental shelves*, regions where water depths are generally less than 200 m. The seafloor descends from these down to broad flat regions, called *abyssal plains*, at depths of between 4 and 5 km. Elongate submarine mountain belts, known as *mid-ocean ridges*, where water decreases to less than 2.5 km deep, serve to separate abyssal plains from one another. Here and there, individual submarine mountains, *seamounts*, protrude from the seafloor, and some of these rise above the surface as *sea islands*. The deepest parts of the oceans are in elongate troughs, called *trenches*. In the deepest trenches, water can be as deep as 11 km. Note that the total vertical distance between the deepest point in the sea and the highest point on land is 19.8 km, only about 0.3% of the Earth's radius (6,371 km).

What does the surface of the geosphere consist of? The exploratory probes that we send down to the surface make a preliminary analysis and find the following **Earth materials**:

- › **Organic chemicals:** A carbon-containing compound that either occurs in living organisms or has characteristics that resemble compounds in living organisms is an *organic chemical*.
- › **Minerals:** A solid, natural substance in which atoms are arranged in an orderly pattern is a **mineral**. A coherent sample of a mineral that grew to its present shape is a **crystal**. Most minerals are *inorganic* chemicals.
- › **Glasses:** A solid in which atoms are not arranged in an orderly pattern is called *glass*.
- › **Rocks:** An aggregate of mineral crystals or grains, or a mass of natural glass, is called a **rock**. As we'll discuss in Interlude A and succeeding chapters, a rock belongs to one of three main classes: (1) *igneous rocks* develop when hot molten (liquid) rock cools and freezes solid; (2) *sedimentary rocks* form from fragments that break off preexisting rock and become cemented together, or from minerals that precipitate out of a water solution; and (3) *metamorphic rocks* form when preexisting rocks undergo change in response to heat and pressure, to develop new minerals and/or arrangements of minerals.

FIGURE 1.16 This map shows the Earth's topography (variations in land elevation) and bathymetry (variations of ocean-floor depth), and shows where glaciers cover the land (white areas).

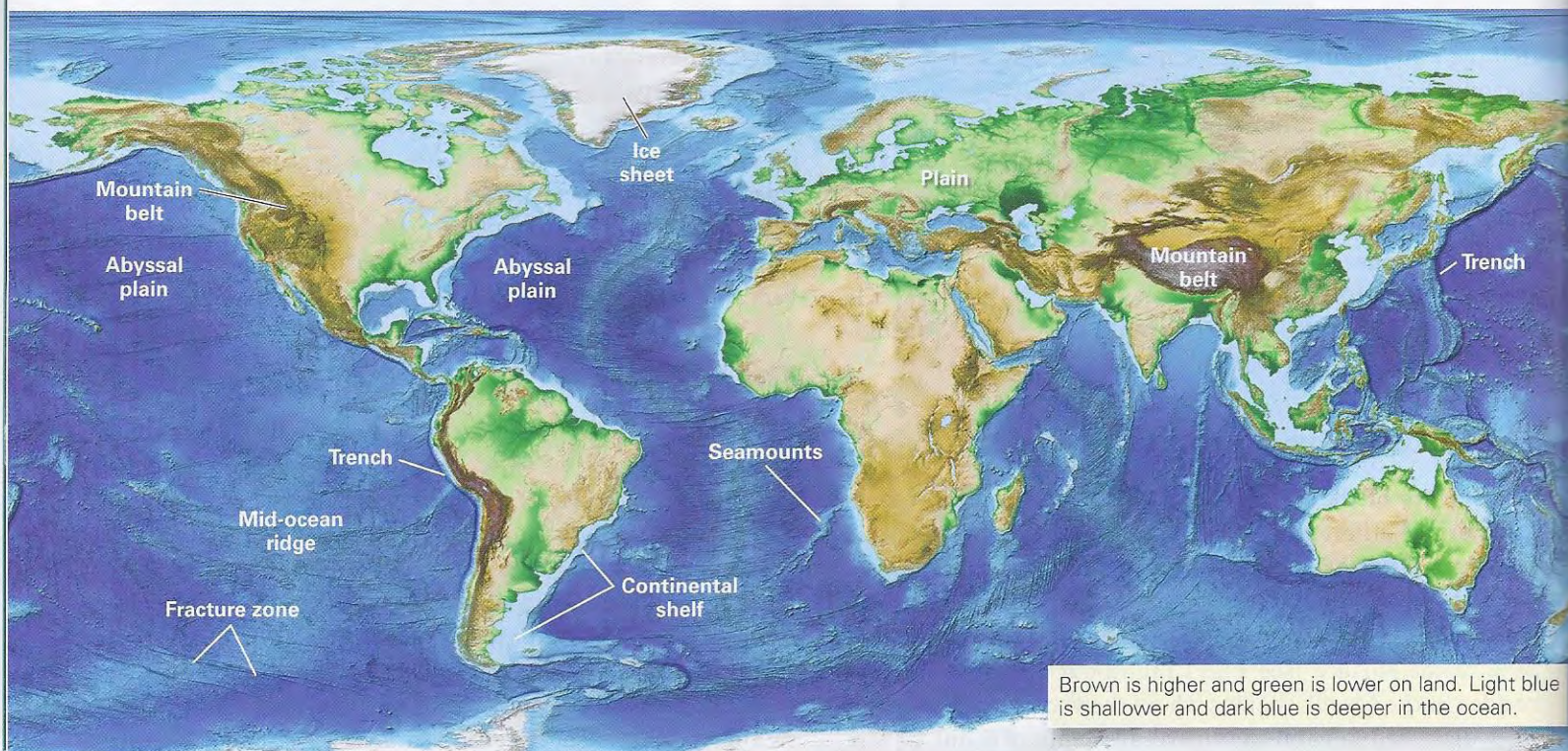
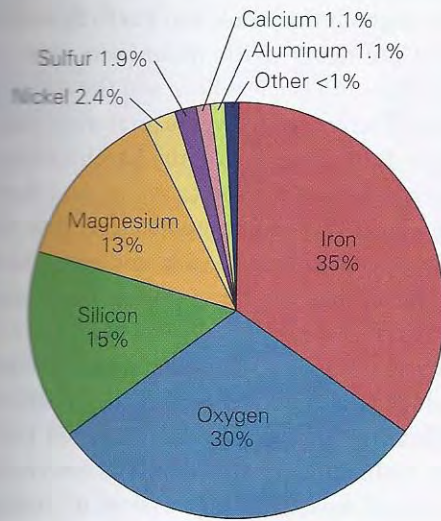


FIGURE 1.17 The proportions of major elements making up the mass of the whole Earth. Note that iron and oxygen account for most of the mass.



Grains: We use the term *grain* either for individual crystals embedded within an igneous or metamorphic rock, or for an individual fragment derived from a once-larger mineral or rock body.

Sediments: An accumulation of unattached mineral grains is called *sediment*.

Metals: A solid composed of metal atoms (such as iron, aluminum, copper, or tin) is called a **metal**. An *alloy* is a mixture containing more than one type of metal atom.

Melts: A **melt** forms when solid materials become hot and transform into liquid. Molten rock is a type of melt—geologists distinguish between *magma*, which is molten rock beneath the Earth's surface, and *lava*, molten rock that has flowed out onto the Earth's surface.

Volatiles: A material that easily transforms into gas at the relatively low temperatures found at the Earth's surface is called a **volatile**.

Of the 92 naturally occurring elements that make up the Earth, 93% of the Earth's mass consists of only four—iron, oxygen, silicon, and magnesium (**Fig. 1.17**). Most of the rock in the geosphere consists of *silicate* minerals, which contain the compound silica (SiO_2), either alone or bonded to other elements. Not surprisingly, rocks composed of silicate minerals are known as **silicate rocks**, which are the most common rocks on Earth. We can distinguish among four types of igneous silicate rocks based on their chemical composition, as defined by the percentage of silica that they contain relative to the percentage of iron oxide and magnesium oxide that they contain. This important ratio determines the density of rocks; rocks with more silica are less dense than rocks with more iron oxide or magnesium oxide. In sequence, from greatest to least proportion of silica, these types are known as *felsic*, *intermediate*, *mafic*, and *ultramafic*. To simplify our discussion of the Earth's layers, we name four common igneous rock types here: (1) *granite*, a felsic rock with large grains; (2) *basalt*, a mafic rock with small grains; (3) *gabbro*, a mafic rock with large grains; and (4) *peridotite*, an ultramafic rock with large grains (**Fig. 1.18**).

SEE FOR YOURSELF...



THE WHOLE EARTH

Latitude

49°18'51.35" N

Longitude

36°48'46.13" W

Zoom to an elevation of 20,000 km (12,400 miles) and look straight down. You can see a view of the whole Earth, showing land, sea, and ice. In this view, clouds have been removed. Green areas are vegetated, tan areas are not.

The Biosphere

The aggregate of all living organisms, as well as the portion of the Earth in which living organisms exist, comprises the **biosphere**. Although most life inhabits the Earth's surface, the

FIGURE 1.18 These are examples of materials that compose the Earth. The left four are types of silicate rocks—granite has the most silica, peridotite the least. The image on the right is a metal alloy.



Granite
density = 2.7 g/cm³



Basalt
density = 2.9 g/cm³



Gabbro
density = 3.0 g/cm³



Peridotite
density = 3.3 g/cm³



Iron-nickel alloy
density = 7.5 g/cm³

Increasing density

biosphere encompasses a region that extends from several kilometers below the Earth's surface, where temperature approaches the boiling point of water, to several kilometers above the surface, where temperature becomes low enough to freeze water. Note that the limits of the biosphere reflect the fact that life, as we know it, survives only under conditions in which liquid water can exist, and that the biosphere overlaps with portions of the geosphere, hydrosphere, and atmosphere.

Even viewed from space, we can see that the Earth's biosphere is extremely complex, and it varies in character both spatially and temporally. Looking down at high magnification, we can distinguish forests, fields, grassland, swamps, and tundra. Based on color changes of land surfaces over the year, we can determine that organisms grow, and then go dormant, during different seasons. And, of course, we would realize from our survey that at least one species has the ability to modify the landscape substantially, by building networks of highways and clusters of buildings, by plowing, digging pits, building mounds, cutting canyons, and damming rivers. Based on the patterns of light at night, we can get a sense of variations in population density, and/or degree of technological sophistication, of this "intelligent life" (Fig. 1.19).

Energy and Exchanges in the Earth System

As we'll see throughout this book, the Earth System is in constant motion. Continents drift, mountains rise, volcanoes spew out lava, rivers and glaciers flow, and the atmosphere and oceans circulate. During these events, materials may transfer within or among different realms of the Earth System. In some cases, materials move from realm to realm, and they may end up back where they began, defining a natural cycle. The energy that drives the movement of rock, air, and water in the Earth System comes from three sources—internal energy, external energy, and gravity.

The term **internal energy** refers to heat (thermal energy) stored or produced inside the Earth. Much of this heat is primordial, originating in processes that formed the Earth in the first place. Collisions of planetesimals converted kinetic energy to thermal energy; compression of matter into a smaller space elevated its temperature; the sinking of iron blobs to form the core generated heat when the blobs rubbed against their surroundings as they sank; and each time a radioactive atom inside the Earth decays, it generates heat. Earth's internal energy ultimately can cause rock to melt, which can thus trigger volcanism. Internal energy keeps

FIGURE 1.19 The lights of the Earth as seen at night from space. This image gives a sense of the distribution of human society, and of variations and industrialization.



BOX 1.3 Consider This...

Journey to the Center of the Earth?

Since ancient times, people have speculated about what's inside our planet. What is the source of incandescent lavas that spew from volcanoes, of precious gems and metals found in mines, of sparkling mineral waters that bubble from springs, and of the mysterious forces that shake the ground and topple buildings? The cultures of ancient Greece and Rome considered the subsurface to be the underworld, Hades, home of the dead, a region of fire and sulfurous

fumes. Perhaps this image was inspired by the molten rock and smoke emitted by the volcanoes of the Mediterranean region. In the 18th and 19th centuries, European writers thought the Earth's interior resembled a sponge containing open caverns variously filled with molten rock, water, or air. In fact, in the popular 1864 novel *Journey to the Center of the Earth*, by the French author Jules Verne, three explorers hike through interconnected caverns down to the Earth's center. Such

a journey is impossible, as there are no caverns below a depth of several kilometers. Even with modern technology, we can't dig or drill down very far. Indeed, the deepest mine penetrates only about 3.5 km beneath the surface of South Africa, and the deepest drill hole probes only 12 km below the surface of northern Russia. Compared with the 6,371 km radius of the Earth, this hole goes less than 0.2% of the way to the center and is nothing more than a pinprick.

portions of the Earth's interior soft enough to flow, allowing pieces of its relatively rigid shell to move relative to one another, and these movements, in turn, lead to mountain building.

External energy is energy reaching the Earth's surface from outside. Most of this energy comes in the form of radiation from the Sun. This energy warms the atmosphere, oceans, and the land surface. External energy, acting together with gravity, causes convection of the atmosphere and hydrosphere, resulting in winds, waves, and currents, and therefore, it also causes transfer of water from the oceans to the land surface, feeding rivers and glaciers that flow over and grind away or **erode** the land surface.

TAKE-HOME MESSAGE

Geologists use the term *Earth System* to refer to the variety of interacting realms in, on, and around the planet. Thirty percent of the surface is land, while 70% is sea. Both the land surface and seafloor display notable variations in elevation and depth, respectively, but the difference between the highest point and the lowest is only about 0.3% of Earth's radius. The solid Earth consists of many materials, the most common of which is silicate rock.

QUICK QUESTION How do we distinguish among types of silicate rocks?

1.7 Looking Inward— Discovering the Earth's Interior

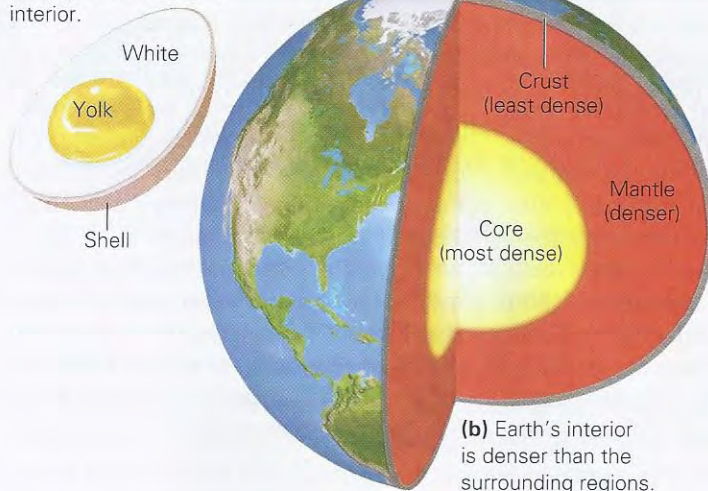
Having mapped the Earth's surface from our spacecraft, we've now got a clear understanding that the planet is a variable and dynamic place. Our final task is to determine what's inside. We begin by describing basic characterizations of the Earth's interior that can be determined from outside the planet (**Box 1.3**). Then, we refine the image by placing instruments on the Earth's surface.

Clues from Examining the Earth's Shape and Density

By making measurements of the gravitational pull of the Earth, and by determining the Earth's volume, we can calculate its *average density*. A quick comparison shows that this average density exceeds the density of common rocks found on the Earth's surface, so the interior of the Earth must contain denser material than its outermost layer, without open space. In fact, we find that the overall mass of the Earth is so great that the planet must contain a large amount of metal. And since the Earth is close to being a sphere, the metal must be concentrated near the center—otherwise, centrifugal force due to the spin of the Earth on its axis would pull the equator

FIGURE 1.20 An early image of Earth's internal layers.

(a) The hard-boiled egg analogy for the Earth's interior.



outward and the planet would become somewhat disk-shaped. (To picture why, consider that when you swing a hammer, your hand feels more force if you hold the end of the light wooden shaft, rather than the heavy metal head.) Further, the interior must be mostly solid, because if it weren't, the land surface would rise and fall due to tidal forces much more than it does, as the Moon orbits the planet.

With these key observations on hand, we conclude that the Earth resembles a hard-boiled egg, in that it has three principal layers: a not-so-dense *crust* (like an eggshell), a denser solid *mantle* in the middle (like an egg white), and a very dense *core* (the egg yolk) (**Fig. 1.20**). We can determine the composition of the crust by sampling. But to determine the character of materials make up the mantle and core, we must study the composition of meteorites (**Box 1.4**), for they provide samples from the differentiated interiors of planetesimals, or protoplanets, that likely resemble the interior of the Earth.

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 feet) and look straight down.

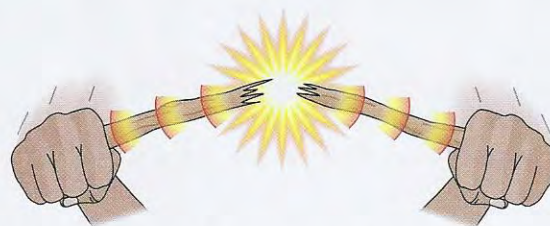
You are seeing Meteor Crater, Arizona, which is 1.2 km across and 180 m deep. It formed in response to the impact of a 40- to 50-m-wide asteroid fragment, less than 50,000 years ago.

Clues from Studying Seismic Waves: Refining the Image

Clearly, many questions remain after our initial survey. Exactly how thick are the Earth's internal layers, and are the boundaries between layers sharp or gradational? We can gain insight into these questions by studying *seismic waves*, vibrations or shocks that pass through the Earth from a location where rock suddenly breaks and slips along a fracture called a *fault* (**Fig. 1.21a**). You can simulate this process of generating vibrations, at a small scale, when you break a stick and feel the snap in your hands (**Fig. 1.21b**). Where seismic waves reach the surface of the Earth, and cause it to shake, people feel an **earthquake**. Study of seismic waves reveals the character of the Earth's insides much as ultrasound measurements help doctors study the insides of a patient, for seismic waves travel at different velocities through different materials, and bend or reflect when they reach boundaries between different materials. To study these waves, we need to place *seismometers*, instruments that can detect seismic waves, at various sites on the Earth's surface. Using methods described in Chapter 8 and Interlude D, records made by our

FIGURE 1.21 Faulting and the generation of seismic waves.

(a) When the rock inside the Earth suddenly breaks and slips on a fault, it generates seismic waves that pass through the Earth. When they reach the surface, we feel an earthquake.



(b) You are feeling seismic waves, in effect, when you snap a stick. The vibrations pass through the stick to your hands.

BOX 1.4 Consider This...

Meteors and Meteorites

Collisions of objects from space with the Earth happened frequently during the early history of the Earth. But even today collisions with space objects continue, and an average of over 1,000 tons of material (rock, metal, dust, and ice) fall to Earth every year.

FIGURE Bx1.4 Meteors and meteorites.



(a) A shower of meteors over Hong Kong in 2001.



(c) Examples of stony meteorites (left) and iron meteorites (right).

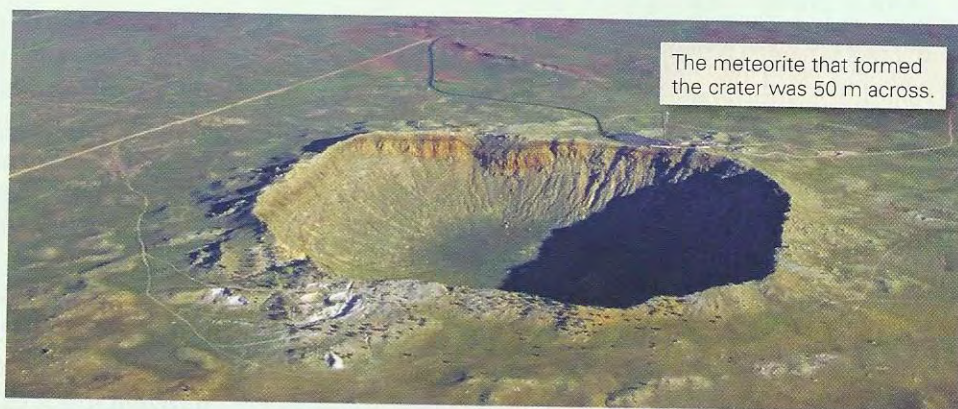
Occasionally, a much bigger object strikes the Earth. The vast majority of this colliding material consists of fragments derived from comets and asteroids sent careening into the path of the Earth after billiard-ball-like collisions with each other out in space, or because the gravitational pull of a passing planet deflected their orbit. Some of the material, however, consists of chips of the Moon or Mars, ejected into space when large objects collided with those bodies.

Astronomers refer to any object from space that enters the Earth's atmosphere as a *meteoroid*. Meteoroids move at speeds of 20 to 75 km/s (over 45,000 mph), so fast that when they reach an altitude of about 150 km, friction with the atmosphere causes them to heat up and vaporize, leaving a streak of bright, glowing gas. The glowing streak, an atmospheric phenomenon, is a **meteor**, also known colloquially, though incorrectly, as a falling star (Fig. Bx1.4a). Most visible meteors completely vaporize by an altitude of about 30 km. But dust-sized ones may slow down sufficiently to float to Earth, and larger ones (fist-sized or bigger) can survive the heat of entry to reach the surface of the

planet. In some cases, meteoroids explode in brilliant fireballs.

Objects that strike the Earth are called **meteorites**. Although almost all meteorites are small and have not caused notable damage on Earth during human history, a very few have smashed through houses, dented cars, and bruised people. During the longer term of Earth history, however, some catastrophic collisions have left huge craters (Fig. Bx1.4b).

Researchers recognize three basic classes of meteorites: *iron* (made of iron-nickel alloy), *stony* (made of rock), and *stony iron* (rock embedded in a matrix of metal). Of all known meteorites, about 93% are stony and 6% are iron (Fig. Bx1.4c). Researchers have concluded that most stony meteorites and all iron meteorites are fragments of planetesimals that had differentiated into a metallic core and a rocky mantle before being shattered by collisions with other planetesimals. Most of these appear to be about 4.54 Ga. A few stony meteorites were derived from planetesimals that never differentiated into core and mantle sectors, and these are as old as 4.57 Ga—the oldest Solar System materials ever measured.



(b) The Barringer meteor crater in Arizona. It formed about 50,000 years ago and is 1.1 km in diameter.

seismometers allow us to pinpoint the depth of boundaries between layers, to identify sublayers within the major layers, and to determine whether layers are solid or liquid.

Pressure and Temperature Inside the Earth

The mass of the overlying rock layer increases with depth, so the pressure within the Earth also increases progressively with depth. In solid rock, the pressure at a depth of 1 km is about 300 atm, so a mine tunnel requires an appropriate support structure to prevent collapse. At the Earth's center, pressure probably reaches about 3,600,000 atm.

Did you ever wonder...
how hot it gets at the center of this planet?

Temperature also increases with depth in the Earth. Even on a cool winter's day, if we could descend down into the crust, we would find that at almost 4 km below the surface, the depth of the deepest gold mine on Earth, the surrounding rock is 60°C (140°F). (At these temperatures, humans can survive no more than 10 minutes, without air-conditioning.) We refer to the rate of change in temperature with depth as the **geothermal gradient**. In the upper part of the crust, the geothermal gradient averages between 20° and 30°C per kilometer. At greater depths, the gradient decreases to 10°C/km or less. Thus, 35 km below the surface of a continent, the temperature reaches 400°C to 700°C, and the mantle-core boundary is about 3,500°C. No one will ever be able to measure the temperature at the Earth's center, but calculations suggest it may exceed 4,700°C, not much cooler than the Sun's surface temperature of 5,500°C.

TAKE-HOME MESSAGE

Measurements of the Earth's mass, shape, and tidal response led to the conclusion that the Earth has three principal internal layers—the crust, the mantle, and the core. Study of earthquake waves passing through the interior has refined this image.

QUICK QUESTION What can we learn about the Earth by studying meteorites?

We will be using this information in the next chapter's discussion of plate tectonics, geology's grand unifying theory. Later, after we have thoroughly discussed earthquakes and seismic waves, we will add further details to our image of the interior in Interlude D.

The Crust

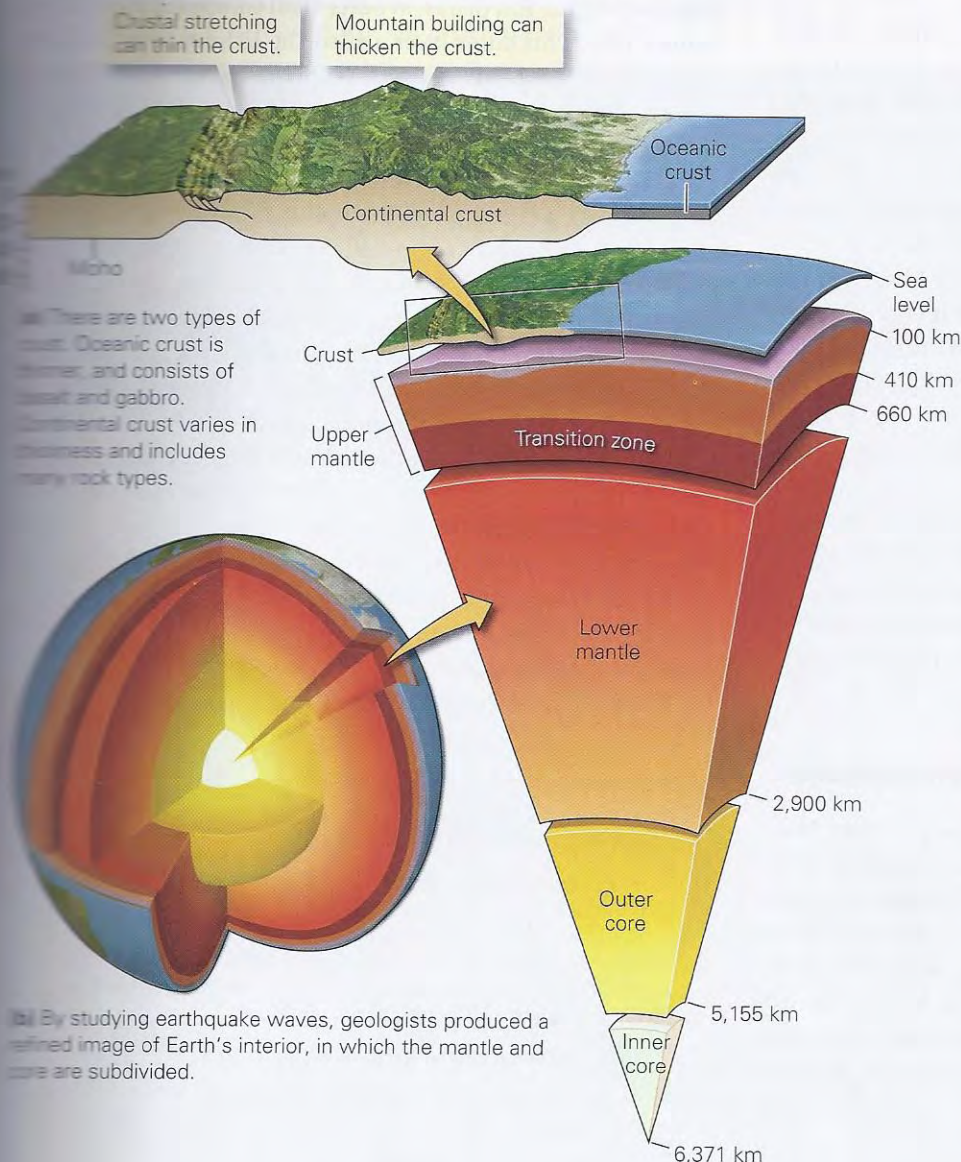
When you look at the surface of the Earth, you are standing on top of its outermost layer, the **crust** (Fig. 1.22a). This layer of the Earth overlaps with the biosphere, and is the source of all of humanity's resources. How thick is this all-important crust? Or, in other words, what is the depth to the crust-mantle boundary? An answer came from the studies of Andrija Mohorovičić (1857-1936), a researcher working in Zagreb, Croatia. In 1909, he discovered that the velocity of earthquake waves suddenly increased at a depth of tens of kilometers beneath the Earth's surface, and he suggested that this increase was caused by an abrupt change in the properties of rock (see Interlude D for further details). Later studies showed that this change can be found most everywhere around our planet, though it occurs at different depths in different locations. Specifically, the area of change is deeper beneath continents than beneath oceans. Geologists now consider the change to define the base of the crust, and they refer to it as the **Moho** in Mohorovičić's honor. The relatively shallow depth of the Moho (7 to 70 km, depending on location), as compared to the radius of the Earth (6,371 km), emphasizes that the crust is very thin indeed. In fact, the crust is only 0.1% to 1.0% of the Earth's radius, so if the Earth were the size of a balloon, the crust would be about the thickness of the balloon's skin.

The crust is not simply cooled mantle, like the skin on chocolate pudding, but rather consists of a variety of rocks that differ in composition (chemical makeup) from mantle rock. Oceanic crust, which underlies the seafloor, is only 7 to 10 km thick—at highway speeds (100 km per hour), you could drive a distance equal to the thickness of the oceanic crust in about 5 minutes. The top of the oceanic crust is composed of a blanket, generally less than 1 km thick, of sediment—clay and tiny shells that settled out of the sea like snow. Beneath this blanket, the oceanic crust consists of a layer of basalt and, below that, a layer of gabbro. Continental crust, in contrast, is generally 35 to 40 km thick (four to five times the thickness of oceanic crust), but its thickness varies significantly. Where continental crust has been stretched, it can be as thin as 25 km, and where it has been squeezed horizontally, it can be up to 70 km thick. Continental crust contains a great variety of rock types, ranging from mafic to felsic in composition. On average, upper continental crust has a felsic (granite-like) to intermediate composition—so continental crust overall is less dense than oceanic crust.

1.8 Basic Characteristics of the Earth's Layers

At this point, we leave our fantasy spacecraft and describe the basic properties of Earth's interior, based on studies that geologists have undertaken during the past 150 years of research.

FIGURE 1.22 A modern view of Earth's interior layers.



(b) By studying earthquake waves, geologists produced a refined image of Earth's interior, in which the mantle and core are subdivided.

Notably, oxygen is the most abundant element in the crust, with silicon a close runner-up, because most rocks contain abundant silica (Table 1.1).

The Mantle

The *mantle* of the Earth forms a 2,885-km-thick layer surrounding the core. In terms of volume, it is the largest part of the Earth (Fig. 1.22b). In contrast to the crust, the mantle consists entirely of an ultramafic (dark and dense) rock called peridotite. This means that peridotite, though rare at the Earth's surface, is actually the most abundant rock in our planet! Seismic-wave velocities change at a depth of 410 km and again at a depth of 660 km in the mantle. Based on this observation, geologists divide the mantle into two sublayers: the *upper mantle*, down to a depth of 660 km, and the *lower mantle*, from 660 km down to 2,900 km. The lower part of the upper mantle, the interval between 410 and 660 km deep, is called the *transition zone*—in this zone, seismic-wave velocities increase in a series of steps, due to abrupt changes in the structure of minerals making up mantle rock.

Almost all of the mantle is solid rock—melt, which occurs in films or bubbles between grains, accounts for just a few percent of its volume, and generally occurs at a depth of 100 to 200 km, only beneath the ocean floor. But even though it's mostly solid, mantle rock below a depth of 100 to 150 km is so hot that it's soft enough to flow, because rock, like wax, softens as it warms up. This flow, however, takes place extremely slowly, at a rate of less than 15 cm a year. So “soft” here does not mean liquid—it simply means that over long periods of time mantle rock can change shape without breaking, a phenomenon known as *plasticity*. Because of its softness, the mantle can undergo convection very slowly. During this convection, warmer mantle rock rises, while cooler mantle rock sinks.

TABLE 1.1 Average Relative Abundances of Elements in the Earth's Crust

Element	Symbol	% by weight	% by volume	% by atoms
Oxygen	O	46.3	93.8	60.5
Silicon	Si	28.0	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5.5	0.5	1.9
Calcium	Ca	3.4	1.0	1.9
Magnesium	Mg	2.8	0.3	1.4
Sodium	Na	2.4	1.2	2.5
Potassium	K	2.3	1.5	1.8
All others	—	1.2	>0.1	3.3

The Core

Early calculations suggested that the core had the same density as gold, so for many years people held the fanciful hope that vast riches lay at the heart of our planet. Alas, geologists eventually concluded that the core consists of a far less glamorous material—iron alloy (iron mixed with 4% nickel, and up to 10% oxygen and/or silicon or sulfur). Studies of seismic waves led geologists to divide the core into two parts (see Fig. 1.22), the *outer core* (between 2,900 and 5,155 km deep) and the *inner core* (from a depth of 5,155 km down to the Earth's center at 6,371 km). The outer core's iron alloy is liquid because the temperature in the outer core is so high that even the great pressures squeezing the region cannot keep atoms locked into a solid framework. The liquid iron alloy's rapid flow generates Earth's magnetic field.

The inner core, with a radius of about 1,220 km, is a solid iron alloy (see Fig. 1.18) that may reach a temperature of over 4,700°C. Even though it is hotter than the outer core, the inner core's alloy remains solid because it is deeper and is subjected to greater pressure, which keeps atoms locked together tightly in solid crystals.

The Lithosphere and the Asthenosphere

So far, we have identified three major layers (crust, mantle, and core) inside the Earth whose compositions differ from each other. Seismic waves travel at different velocities through these layers. An alternative way of thinking about Earth layers comes from studying the degree to which the material of each layer can flow. In this context, we distinguish between *rigid* materials, which can bend or break but cannot flow, and *plastic* materials, which are relatively soft and can flow without breaking.

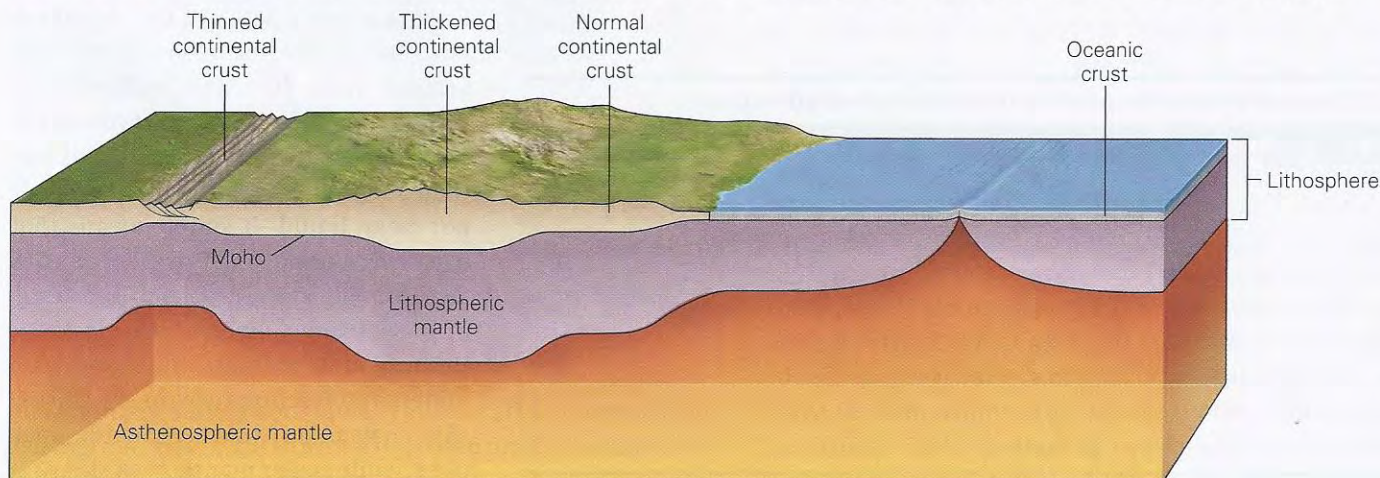
The outer 100 to 150 km of the Earth is relatively rigid. In other words, the Earth has an outer shell composed of rock that cannot flow. This outer layer, called the **lithosphere**, consists of the crust plus the relatively cool uppermost part of the upper mantle (Fig. 1.23). We refer to this portion of the upper mantle as the *lithospheric mantle*. Note that the terms lithosphere and crust are not the same—the crust is only the top layer of the lithosphere. The lithosphere lies on top of the **asthenosphere**, which is the portion of the mantle in which rock is plastic and can flow. The boundary between the lithosphere and asthenosphere occurs where the temperature reaches about 1,280°C, for when temperatures are higher than this, mantle rock becomes soft enough to flow. Note that the asthenosphere is made up entirely of a section of the mantle that generally lies below a depth of 100 to 150 km. We can't assign a specific depth to the base of the asthenosphere because all of the mantle below 150 km can flow, but for convenience, some geologists equate the base of the asthenosphere with the top of the transition zone. As we begin our study of plate tectonics, in the next chapter, we'll see that the movement of plates, whose interaction governs most major geologic phenomena, can take place only because of the ability of the asthenosphere to flow.

TAKE-HOME MESSAGE

Earth's outermost layer, the crust, is very thin; oceanic and continental crust differ in composition. Most of Earth's mass lies in the mantle. A metallic core lies at this planet's center. The crust and the outermost mantle together comprise the rigid lithosphere, while the asthenosphere is the inner mantle whose material can flow.

QUICK QUESTION Is the entire core solid?

FIGURE 1.23 A block diagram of the lithosphere emphasizing the difference between continental and oceanic lithosphere.



Another View Astronomers are discovering many planetary systems around other nearby stars in our galaxy. This is an artist's conception of what the nearest planetary system, Epsilon Eridani, might look like. This example has an asteroid belt and comets. Their tails follow the currents of the stellar wind.



Chapter 1 Review

Chapter Summary

- › The geocentric model of the Universe placed the Earth at the center of the Universe. The heliocentric model placed the Sun at the center.
- › The Earth is one of eight planets orbiting the Sun. The Solar System lies on the outer edge of the Milky Way galaxy. The Universe contains hundreds of billions of galaxies.
- › Most astronomers agree that the Universe has been expanding since it began at the Big Bang, about 13.8 billion years ago.
- › The first atoms (hydrogen and helium) of the Universe developed within minutes of the Big Bang. These atoms formed vast gas clouds, called nebulae.
- › Only very small atoms formed during Big Bang nucleosynthesis. The Earth, and the life forms on it, contain elements that could have been produced only during the life cycle of stars. Thus, we are all made of stardust.
- › Gravity causes clumps of gas in the nebulae to coalesce into flattened disks with bulbous centers. As the central ball of this accretionary disk collapsed inward, it became a warm protostar. Eventually, the ball became so hot and dense that fusion reactions began and it became a true star.
- › Planets developed from the rings of gas and dust surrounding newborn stars. These condensed into planetesimals that then clumped together to form protoplanets, and finally true planets.
- › The Moon formed from debris ejected when a protoplanet collided with the Earth in the very young Solar System.
- › When a protoplanet grows large enough, it eventually becomes warm enough inside to differentiate into a core and mantle, and to assume a near-spherical shape.
- › The Earth has a magnetic field that shields it from solar wind and cosmic rays.
- › A layer of gas surrounds the Earth. This atmosphere, which consists of 78% N₂, 21% O₂, and 1% other gases, can be subdivided into layers. Air pressure decreases with elevation.
- › The surface of the Earth can be divided into land (30%) and ocean (70%).
- › Earth materials include organic chemicals, minerals, glasses, rocks, metals, melts, and volatiles. Most rocks on Earth contain silica (SiO₂). We distinguish among various major rock types based on the proportion of silica.
- › The Earth's interior can be divided into three distinct layers: the very thin crust, the rocky mantle, and the metallic core.
- › Pressure and temperature both increase with depth in the Earth. The rate at which temperature increases as depth increases is the geothermal gradient.
- › The crust is a thin skin that varies in thickness from 7–10 km (beneath the oceans) to 25–70 km (beneath the continents). Oceanic crust is mafic in composition, whereas average upper continental crust is felsic to intermediate. The mantle is composed of ultramafic rock. The core is made of iron alloy.
- › Studies of earthquake waves reveal that the mantle can be subdivided into an upper mantle (including the transition zone) and a lower mantle. The core can be subdivided into the liquid outer core and a solid inner core. Circulation of the outer core produces the Earth's magnetic field.
- › The crust plus the upper part of the mantle constitute the lithosphere, a rigid shell. The lithosphere lies over the asthenosphere, mantle that can flow.

Guide Terms

accretionary disk (p. 18)
asteroid (p. 14)
asthenosphere (p. 38)
atmosphere (p. 28)
bathymetry (p. 30)
Big Bang theory (p. 16)
biosphere (p. 31)
comet (p. 14)
cosmology (p. 11)

crust (p. 36)
cryosphere (p. 29)
crystal (p. 30)
differentiation (p. 23)
dipole (p. 26)
earthquake (p. 34)
Earth materials (p. 30)
Earth System (p. 28)
ecliptic (p. 13)

erosion (p. 33)
expanding Universe theory (p. 15)
external energy (p. 33)
galaxy (p. 13)
geocentric model (p. 12)
geosphere (p. 29)
geothermal gradient (p. 36)
giant planet (p. 13)

groundwater (p. 29)
heat (p. 20)
heliocentric model (p. 12)
hydrosphere (p. 29)
internal energy (p. 32)
lithosphere (p. 38)
magnetic field (p. 26)
magnetosphere (p. 26)
melt (p. 31)



GEOTOURS THIS CHAPTER'S GEOTOUR EXERCISE (A) FEATURES:

- › Nebular Supernova
- › Spiral Galaxy
- › Meteorite Impacts

nebular theory (p. 18)	refractory materials (p. 22)	supernova (p. 19)
nuclear fission (p. 23)	rock (p. 30)	temperature (p. 20)
nuclear fusion (p. 18)	silicate rock (p. 31)	terrestrial planet (p. 13)
planet (p. 13)	Solar System (p. 13)	topography (p. 30)
planetesimal (p. 22)	star (p. 12)	Universe (p. 12)
protoplanet (p. 22)	stellar nucleosynthesis (p. 19)	vacuum (p. 18)
protostar (p. 18)	stellar wind (p. 19)	volatile materials (pp. 21, 31)

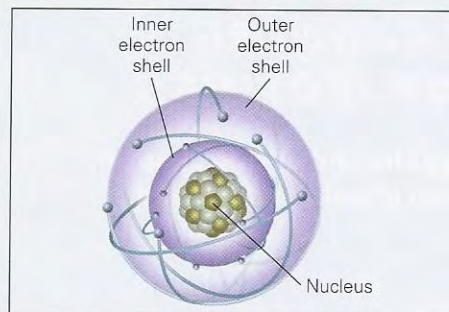
Review Questions

1. Compare the geocentric and heliocentric Universe concepts.
2. What is the ecliptic, and why are the orbits of the planets within the ecliptic? Why is Pluto no longer considered to be a planet?
3. Describe the expanding Universe theory.
4. What is the Big Bang, and when did it start?
5. Describe the steps in the formation of the Solar System according to the nebular theory.
6. Why isn't the Earth homogeneous?
7. Describe how the Moon was formed.
8. Why is the Earth round?
9. What is the Earth's magnetic field? Draw a representation of the field on a piece of paper. What causes aurorae?
10. What is the Earth's atmosphere composed of? Why would you die of suffocation if you were to eject from a fighter plane at an elevation of 12 km without an oxygen tank?
11. What is the proportion of land area to sea area on Earth?
12. Describe the major categories of materials constituting the Earth. On what basis do geologists distinguish among different kinds of silicate rocks?
13. What are the principal layers of the Earth?
14. How do temperature and pressure change with increasing depth in the Earth?
15. What are meteorites, and how does the study of them provide insight into the character of the Earth's interior?
16. What is the Moho? Describe the differences between continental crust and oceanic crust.
17. What is the mantle composed of? Is there any melt in it?
18. What is the core composed of? How do the inner and outer cores differ? Which produces the magnetic field?
19. What is the difference between the lithosphere and asthenosphere? At what depth does the lithosphere-asthenosphere boundary occur? Is this above or below the Moho? Is the asthenosphere entirely liquid?

On Further Thought

1. Are all stars that we see today considered to be first-generation stars? What is the evidence for your answer?
2. Why are the giant planets, which contain abundant gas and ice, farther from the Sun?
3. Recent observations suggest that the Moon has a very small, solid core that is less than 3% of its mass. In comparison, Earth's core is about 33% of its mass. Explain why this difference might exist.
4. The Moon has virtually no magnetosphere. Why?
5. Popular media sometimes imply that the crust floats on a "sea of magma." Is this a correct image of the mantle just below the Moho? Explain your answer.

Online Resources



Videos

This chapter features videos showing how our Solar System and the Earth formed. Other topics covered include nebular theory, proto-Earth, the formation of the Moon, and the beginning of the atmosphere.

Assessment

This chapter features visual labeling exercises on topics such as atomic structures and our Solar System.