4

Origin of the Solar System

Learning Goals

4.1 Characteristics of the Solar System

- What does the solar system look like?
- What features of our solar system provide clues to how it formed?

4.2 The Birth of the Solar System

- What theory best explains the orderly patterns of motion in our solar system?
- How does our theory account for the features of planets, moons, and small bodies?

✽ THE PROCESS OF SCIENCE IN ACTION

4.3 The Age of the Solar System

- How do we determine the age of Earth and the solar system?

From space, we see our world as a small blue oasis set against a black void. Such images have inspired great works of art, music, and poetry, and have come to symbolize global awareness of the environment. Images of Earth also inspire us to ask scientific questions. How did our planet come to be, and why is it such an ideal home for life? We will examine these questions in this and the next chapter. We will see that the answers are best understood by not just studying Earth, but also comparing Earth to other worlds. We'll begin in this chapter by exploring general features of our solar system and how they help us understand the modern scientific theory of the birth of our solar system.

4.1 Characteristics of the Solar System

Our major goal in this chapter is to understand the scientific theory that best explains the origin of Earth and the solar system. To do so, we must first have a good general picture of what the solar system looks like and a basic understanding of its individual worlds. We'll then use these ideas to come up with a list of major features that any successful theory of the solar system's birth must explain.

What does the solar system look like?

Imagine viewing the solar system from beyond the orbits of the planets. What would we see? Without a telescope, the answer would be "not much." Remember that the Sun and planets are all quite small compared to the distances between them [Section 1.1]—so small that if we viewed them from the outskirts of our solar system, the planets would be only pinpoints of light, and even the Sun would be just a small bright dot in the sky. But if we magnify the sizes of the planets by about a million times compared to their distances from the Sun, and show their orbital paths, we get the central picture in **Figure 4.1** (pp. 56–57). **Table 4.1** then summarizes key data for the planets.

Even on first glance, the figure and table make it clear that our solar system is *not* a random collection of worlds. Instead, our solar system shows several clear patterns. For example, all the planets orbit the Sun in the same direction and in nearly the same plane, and the four inner planets are much smaller and closer together than the next four planets. We'll discuss these and other patterns in more detail shortly. First, let's build our general picture of the solar system by taking a brief tour of its major regions, starting with the Sun and moving outward.

Think about it Figure 4.1 and Table 4.1 both indicate the axis tilts of the planets. Based on what you learned about the cause of Earth's seasons in Chapter 2, which planets should have seasons similar to those of Earth? Which planets should have no seasons at all? Which planet should have the most extreme seasonal differences?

The Sun The Sun is by far the largest and brightest object in our solar system. It contains almost 99.9% of the solar system's total mass, making it nearly a thousand times as massive as everything else in the solar system combined. Its mass and brightness also make it the most influential object in our solar system. The Sun's gravity governs the orbits of the planets, and the Sun is the source of virtually all the visible light in our solar system, since the Moon and planets shine only by virtue of the sunlight they reflect. It is also the primary influence on the temperatures of planetary surfaces and atmospheres. Charged particles flowing outward from the Sun (which make up the *solar wind*) help shape planetary magnetic fields and can influence planetary atmospheres. Nevertheless, we can understand the planets without knowing further details about the Sun, so we'll save these details for our study of the Sun as a star in Chapter 8.

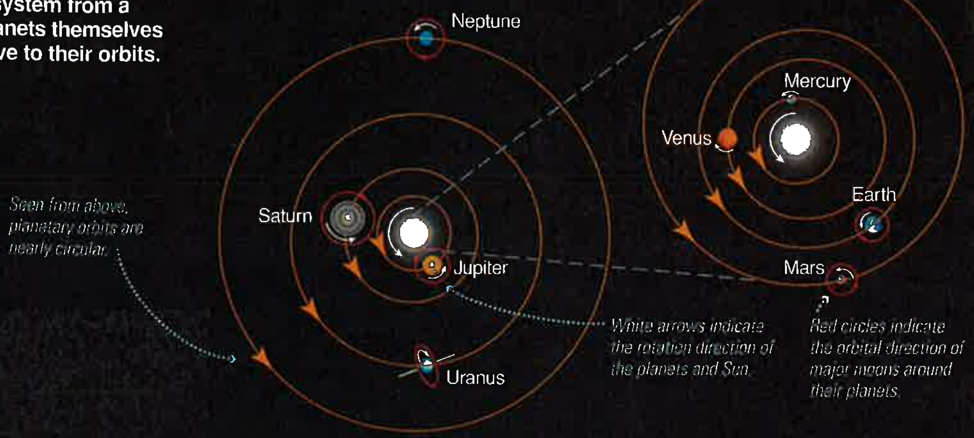
The Inner Planets The four inner planets—Mercury, Venus, Earth, and Mars—are all quite small and close together compared to the outer planets. These four planets also share similar compositions of metal and rock, which is why we often refer to them as the **terrestrial planets.** (*Terrestrial* means "Earth-like.")

Despite their similarities in composition, the four terrestrial planets differ substantially in their details. Mercury is a desolate, cratered world that looks much like our own Moon. Venus, nearly identical in size to Earth, is best known for its extreme temperature and pressure: Its thick, carbon dioxide

Cosmic Context Figure 4.1: The Solar System

The solar system's layout and composition offer four major clues to how it formed. The main illustration below shows the orbits of planets in the solar system from a perspective beyond Neptune, with the planets themselves magnified by about a million times relative to their orbits.

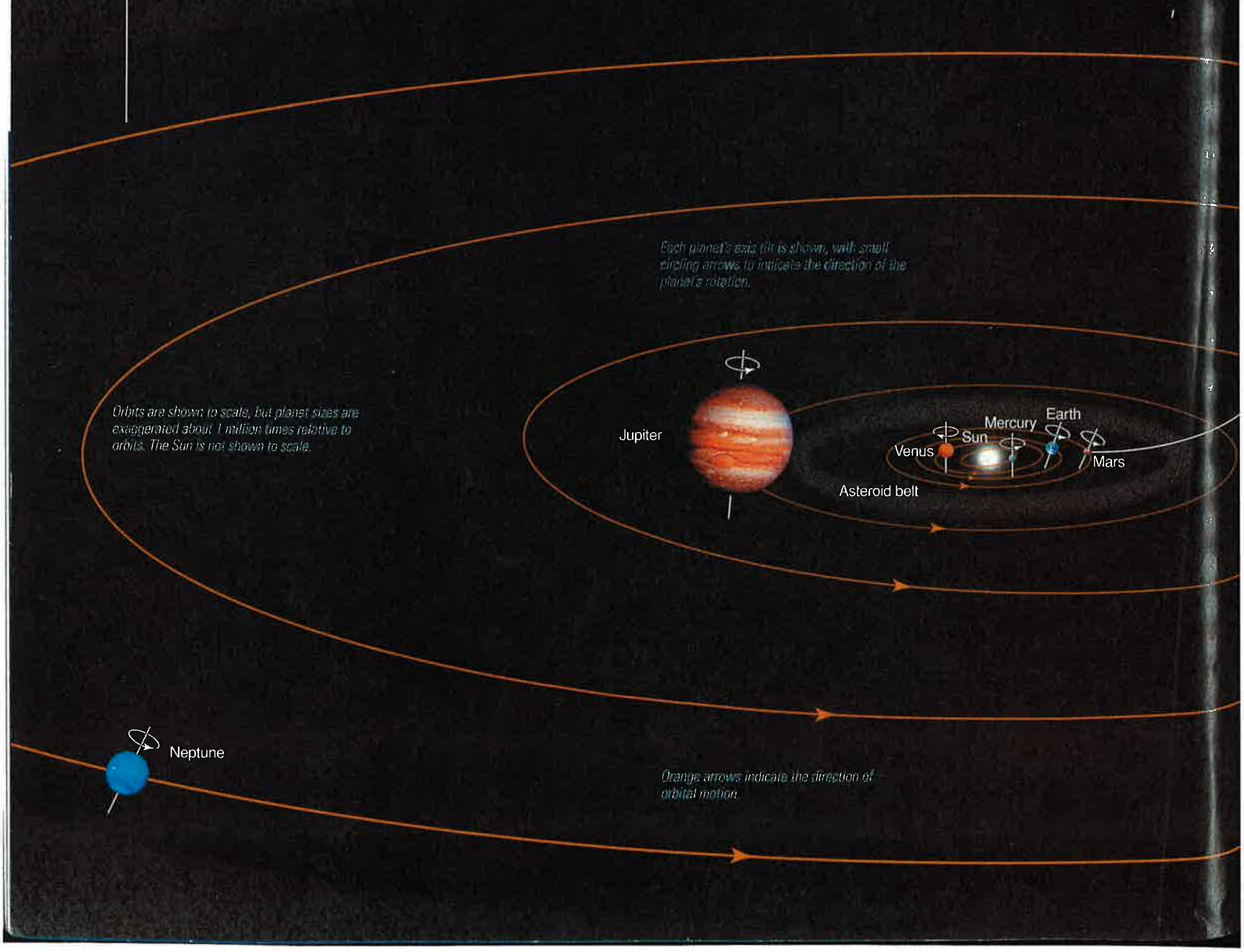
① **Large bodies in the solar system have orderly motions.** All planets have nearly circular orbits going in the same direction in nearly the same plane. Most large moons orbit their planets in this same direction, which is also the direction of the Sun's rotation.



Seen from above, planetary orbits are nearly circular.

White arrows indicate the rotation direction of the planets and Sun.

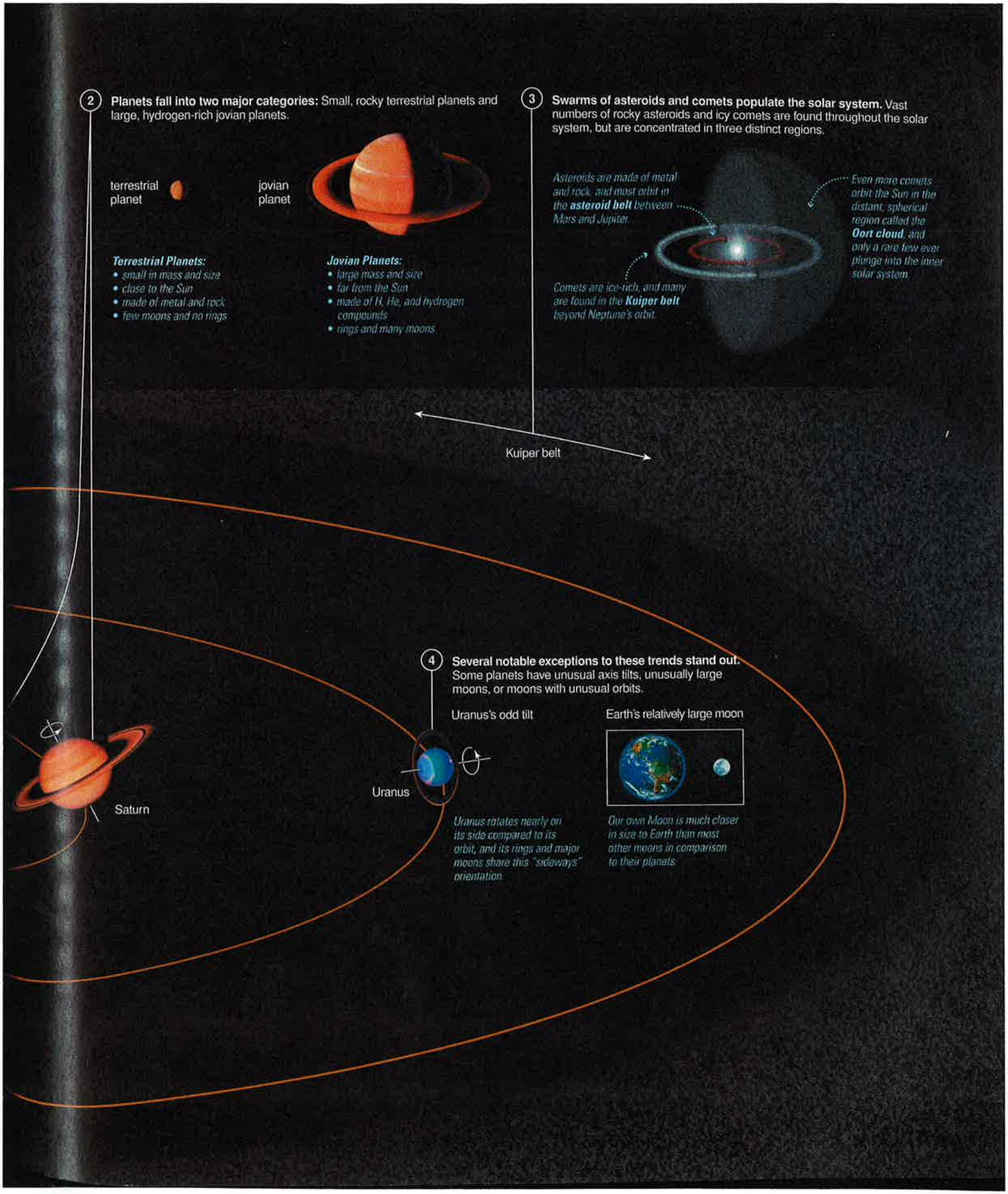
Red circles indicate the orbital direction of major moons around their planets.



Each planet's axis tilt is shown, with small circling arrows to indicate the direction of the planet's rotation.

Orbits are shown to scale, but planet sizes are exaggerated about 1 million times relative to orbits. The Sun is not shown to scale.

Orange arrows indicate the direction of orbital motion.



② **Planets fall into two major categories:** Small, rocky terrestrial planets and large, hydrogen-rich jovian planets.

Terrestrial Planets:

- *small in mass and size*
- *close to the Sun*
- *made of metal and rock*
- *few moons and no rings*

Jovian Planets:

- *large mass and size*
- *far from the Sun*
- *made of H, He, and hydrogen compounds*
- *rings and many moons*

③ **Swarms of asteroids and comets populate the solar system.** Vast numbers of rocky asteroids and icy comets are found throughout the solar system, but are concentrated in three distinct regions.

Asteroids are made of metal and rock, and most orbit in the ***asteroid belt*** *between Mars and Jupiter.*

Even more comets orbit the Sun in the distant, spherical region called the ***Oort cloud****, and only a rare few ever plunge into the inner solar system.*

Comets are ice-rich, and many are found in the ***Kuiper belt*** *beyond Neptune's orbit.*

④ **Several notable exceptions to these trends stand out.** Some planets have unusual axis tilts, unusually large moons, or moons with unusual orbits.

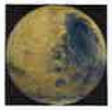
Uranus's odd tilt

Uranus rotates nearly on its side compared to its orbit, and its rings and major moons share this "sideways" orientation.

Earth's relatively large moon

Our own Moon is much closer in size to Earth than most other moons in comparison to their planets.

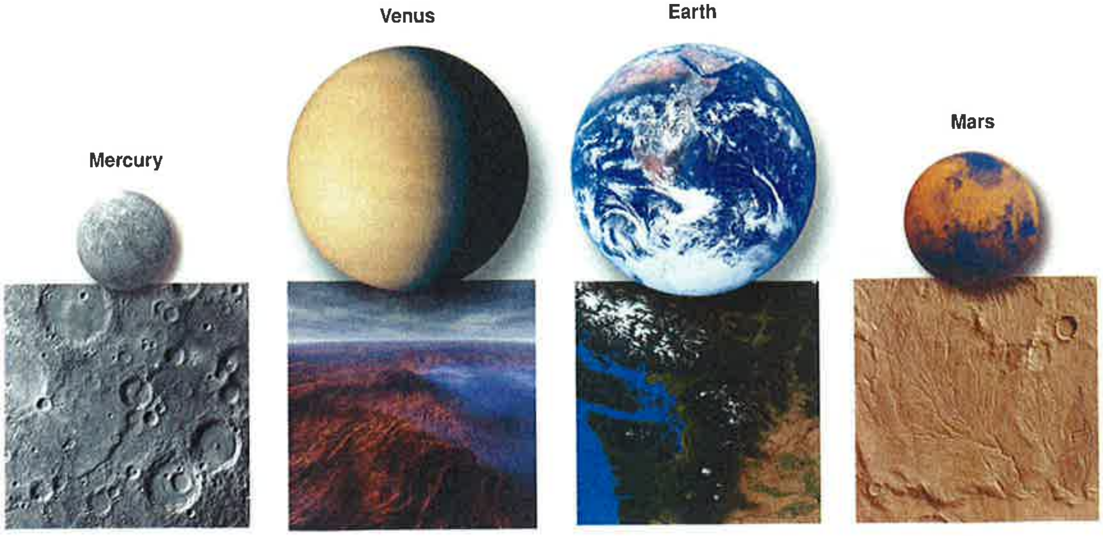
Table 4.1 Planetary Data*

Photo	Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/m^3)	Orbital Period	Rotation Period	Axis Tilt	Average Surface (or Cloud-Top) Temperature[†]	Composition	Known Moons (2008)	Rings?
	Mercury	•	0.387	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night)	Rocks, metals	0	No
	Venus	•	0.723	6051	0.82	5.24	225 days	243 days	177.3°	740 K	Rocks, metals	0	No
	Earth	•	1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
	Mars	•	1.52	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
	Jupiter	●	5.20	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds[§]	63	Yes
	Saturn	●	9.54	60,268	95.2	0.70	29.4 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds[§]	60	Yes
	Uranus	●	19.2	25,559	14.5	1.32	83.8 years	17.2 hours	97.9°	60 K	H, He, hydrogen compounds[§]	27	Yes
	Neptune	●	30.1	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds[§]	13	Yes
	Pluto	·	39.5	1160	0.0022	2.0	248 years	6.39 days	112.5°	40 K	Ices, rock	3	No
	Eris	·	67.7	1200	0.0028	2.3	557 years	?	?	?	Ices, rock	1	?

*Including the dwarf planets Pluto and Eris.

[†] Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed.

[§] Includes water (H_2O), methane (CH_4), and ammonia (NH_3).



a Heavily cratered Mercury also has smooth volcanic plains and "wrinkles" that are steep cliffs.

b Artist's rendering of Venus's surface as it might appear to our eyes.

c A portion of Earth's surface as it appears without clouds.

d Mars has features that look like dry riverbeds; you can also see impact craters.

Figure 4.2 | The terrestrial planets, shown to scale, along with views highlighting key features.

atmosphere bakes Venus's surface to an incredible 470°C (about 880°F; see Appendix C.6 for a review of temperature scales) while creating a surface pressure equivalent to what exists nearly a kilometer (0.6 mile) beneath the ocean's surface on Earth. Our home planet, Earth, is the only world in our solar system with surface oceans of liquid water. Mars, though it lacks any surface liquid water today, shows clear evidence of having had flowing water in its distant past, which is why scientists are so interested in the search for past or present life on Mars. **Figure 4.2** shows the four terrestrial planets to scale, along with views highlighting some of their features.

The Asteroid Belt If you look closely at Figure 4.1, you'll see a donut-shaped region of dots between the orbits of Mars and Jupiter. These dots represent some of the more than 400,000 known asteroids that make up the **asteroid belt.** An **asteroid** is essentially a chunk of metal and rock that orbits the Sun much like a planet, but it is much smaller in size (**Figure 4.3**). Despite their large numbers, the total mass of all the asteroids combined is much smaller than the mass of our Moon. Moreover, despite what you may have seen in movies, asteroids are spread out over such a large region of space that there would be little danger of hitting one if you flew a spaceship through the asteroid belt.

The Outer Planets Beyond the asteroid belt we encounter the realm of the four outer planets: Jupiter, Saturn, Uranus, and Neptune. These planets are much larger and much farther apart than the terrestrial planets. They are also very different in composition from the terrestrial planets, because they contain vast amounts of materials that would be gaseous on Earth, including hydrogen, helium, and *hydrogen compounds* such as water (H_2O), methane (CH_4), and ammonia (NH_3). Their gaseous compositions mean they have no solid surfaces; instead, if you entered any of their atmospheres, you would simply plunge deeper and deeper into the interior until you were crushed by the growing gas pressure. Because Jupiter is the largest of this group of planets, we refer to them jointly as **jovian planets.** (*Jovian* means "Jupiter-like.")

The jovian planets also differ from the terrestrial planets in another important way: While the terrestrial planets have only three moons among

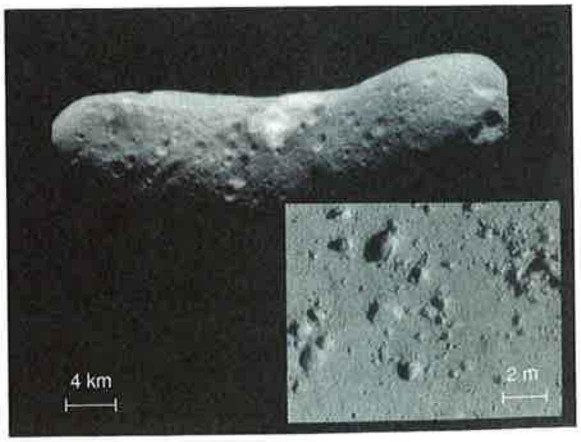
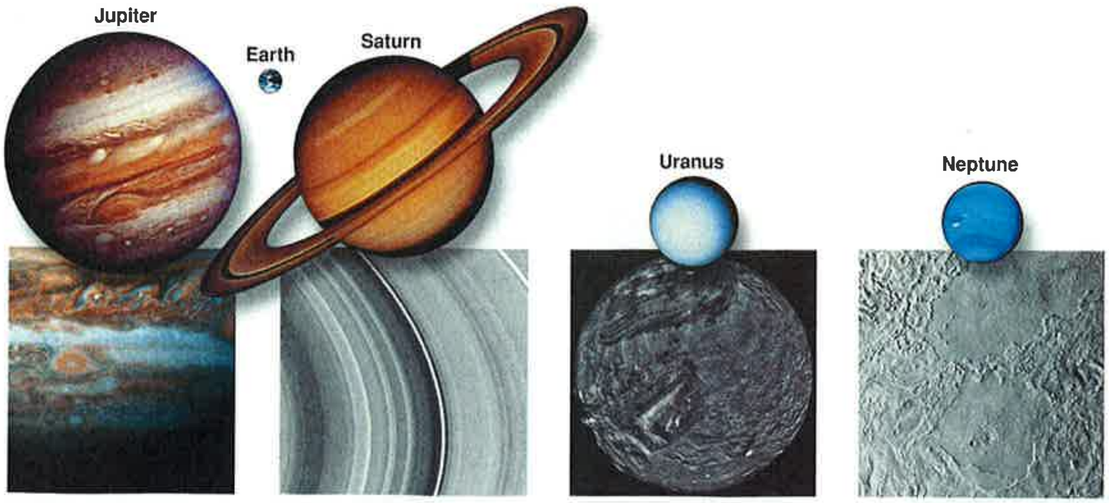


Figure 4.3 | The asteroid Eros, photographed from the *NEAR* spacecraft, is probably typical of small asteroids in appearance. The inset shows its surface, on which *NEAR* landed at the end of its mission.



a Jupiter's atmosphere shows intricate cloud patterns and oval-shaped storms.

b Saturn's rings are made of countless small particles, each orbiting Saturn independently.

c Uranus's moon Miranda shows evidence of past geological activity.

d Neptune's moon Triton has impact craters filled by eruptions of ice volcanoes.

Figure 4.4 | The jovian planets shown to scale, with Earth for comparison, along with selected features of the planets, rings, or moons.

them (one for Earth and two very small moons for Mars), the jovian planets each have many moons. Many of these moons are amazing worlds in their own right. For example, Jupiter's moon Io is the most volcanically active world in our solar system, and its moon Europa is thought to have a deep subsurface ocean of liquid water. Saturn's moon Titan is the only moon in the solar system with a thick atmosphere, and its surface contains cold lakes of liquid ethane or methane. In addition to moons, all four jovian planets are orbited by vast numbers of small particles that make up their **rings,** although only Saturn's rings are easily visible from Earth. **Figure 4.4** shows the four jovian planets to scale, along with representative views including rings and moons.

Realm of the Comets People throughout history have been intrigued and inspired by the occasional appearance of a **comet** in our skies (**Figure 4.5**). Comets are made of rock and ice, so when they enter the inner solar system they can grow spectacular *tails* as ice vaporizes and escapes into space.

The comets that we see in the sky must come from somewhere, and study of their orbital paths has led scientists to conclude that they come from two

Figure 4.5 | Comet McNaught and the Milky Way over Patagonia, Argentina, in 2007. (The fuzzy patches above the comet tail are the Small and Large Magellanic Clouds, which are satellite galaxies of the Milky Way.)

vast reservoirs of comets that reside at great distances from the Sun. The first reservoir, known as the **Kuiper belt** (*Kuiper* rhymes with *piper*), is the donut-shaped region represented by the dots beyond the orbit of Neptune in Figure 4.1. The Kuiper belt is thought to contain more than 100,000 comets. Some of these "comets" are large enough for their own gravity to make them round in shape, which qualifies them as *dwarf planets;* as we discussed in Section 1.3, Pluto and Eris are examples of dwarf planets in the Kuiper belt.

The second reservoir of comets is called the **Oort cloud** (*Oort* rhymes with *court*). It is roughly spherical in shape, and its outer regions may extend to nearly one-quarter of the distance to the nearest stars. The Oort cloud is so far from the Sun that our telescopes are not yet capable of seeing the comets that reside within it, but study of comets that come from this region tells us that it may contain as many as a trillion comets.

What features of our solar system provide clues to how it formed?

Having completed our brief tour of the solar system, we now see our solar system as a family of worlds, with a variety of "family traits" that must be explained by any theory of our solar system's formation. More specifically, we can identify four major features of the solar system's family of worlds, each of which is associated with one of the numbered steps in Figure 4.1.

Feature 1: Patterns of Motion Figure 4.1 shows several clear patterns of motion among the large bodies of our solar system. For example:

- All planetary orbits are nearly circular and lie nearly in the same plane.
- All planets orbit the Sun in the same direction: counterclockwise as viewed from high above Earth's North Pole.
- Most planets rotate in the same direction in which they orbit (counterclockwise as viewed from above the North Pole), with fairly small axis tilts. The Sun also rotates in this same direction.
- Most of the solar system's large moons exhibit similar properties in their orbits around their planets, such as orbiting in their planet's equatorial plane in the same direction that the planet rotates.

Together, these orderly patterns represent the first major feature of our solar system. As we'll see shortly, our theory of solar system formation explains these patterns as consequences of processes that occurred during the early stages in the birth of our solar system.

Feature 2: Two Types of Planets Our brief planetary tour showed that the planets come in two major types: the relatively small and rocky *terrestrial planets* and the larger and more gaseous *jovian planets.* **Table 4.2** contrasts the general traits of these two types of planets.

Why do the planets come in these two distinct types? As we will see, the answer has to do with temperatures in the solar system at the time during which the planets formed: The rocky terrestrial planets formed in the hotter inner regions of the solar system, while the larger jovian planets—which tend to have icy moons—formed in the colder outer regions.

Feature 3: Asteroids and Comets We have found that while the Sun and planets are the most massive objects in the solar system, they are far outnumbered by smaller bodies: rocky *asteroids* and icy *comets.* Moreover, rather than being randomly spread throughout the solar system, these small bodies are found mainly in three regions: Most asteroids orbit the Sun within the *asteroid*

Table 4.2 Comparison of Terrestrial and Jovian Planets

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density	Lower density
Made mostly of rock and metal	Made mostly of hydrogen, helium, and hydrogen compounds
Solid surface	No solid surface
Few (if any) moons and no rings	Rings and many moons
Closer to the Sun (and closer together), with warmer surfaces	Farther from the Sun (and farther apart), with cool temperatures at cloud tops

Tools of Science: Conservation Laws

A candy bar looks quite different if you smash it into little pieces, but the total amount of candy remains the same no matter how it breaks apart. In science, we would say that the total amount of candy is *conserved*, and we could say that the process of smashing the candy bar obeys a "law of conservation of candy." While candy conservation is somewhat obvious, scientists have discovered other conservation laws that reveal deep secrets of nature. Here we'll discuss two that are especially important in astronomy.

The **law of conservation of energy** tells us that energy cannot appear out of nowhere or disappear into nothingness. Objects can gain or lose energy only by exchanging energy with other objects. Energy can change forms, however, so we must know some of the different forms that energy can take (**Figure 1**):

- **Kinetic energy** is energy of motion. Falling rocks, orbiting planets, and cyclists in motion all have kinetic energy in an amount that depends on the object's mass and speed. Note that individual atoms and molecules are always in motion and therefore also have kinetic energy; the collective kinetic energy of many individual particles in a substance like a rock or in the air is called **thermal energy.**
- **Potential energy** is stored energy that might later be converted into some other form. For example, a rock perched on a ledge has **gravitational potential energy** because it will fall if it slips off the edge, and food contains **chemical potential energy** that can be converted into the kinetic energy of the moving cyclist. Einstein discovered that mass itself is a form of potential energy, often called **mass-energy:** the amount of mass-energy in an object of mass m is given by Einstein's famous equation $E = mc^2$.
- **Radiative energy** is energy carried by light. (The word *radiation* is often used as a synonym for *light.*) All light carries energy, which is why light can affect molecules in our eyes—thereby allowing us to see—or warm the surface of a planet.

A couple of examples should help clarify the idea of energy conservation. Consider a rock that falls off a ledge. Before it falls, it has gravitational potential energy by virtue of its height, but no kinetic energy because it is not moving. As it falls, its gravitational potential energy gradually turns into kinetic energy, so the rock accelerates as it falls. Next consider the Sun, which sends radiative energy into space as it shines. This radiative energy is generated by nuclear fusion in the Sun's core, which releases some of the mass-energy stored in the Sun's hydrogen.

A second important conservation law for astronomy is the **law of conservation of angular momentum.** To understand this law, think about a spinning ice skater (**Figure 2**). We say that she has angular momentum due to the fact that she is spinning, and the amount of angular momentum she has is described by the formula $m \times v \times r$, where m is her mass, v is her velocity as she spins, and r is her "radius" represented (approximately) by how far she extends her arms as she spins. Because there is little friction on the ice to slow her down, the law of conservation of angular momentum tells us that her angular momentum must stay the same no matter what she does with her arms. If she pulls her arms in, thereby decreasing her radius, her velocity of spin must increase to keep the product $m \times v \times r$ constant. For an astronomical example, consider a contracting cloud of interstellar gas: Because its radius decreases as it shrinks in size, its rate of spin must increase in order to keep its angular momentum unchanged.

Energy can be converted from one form to another.

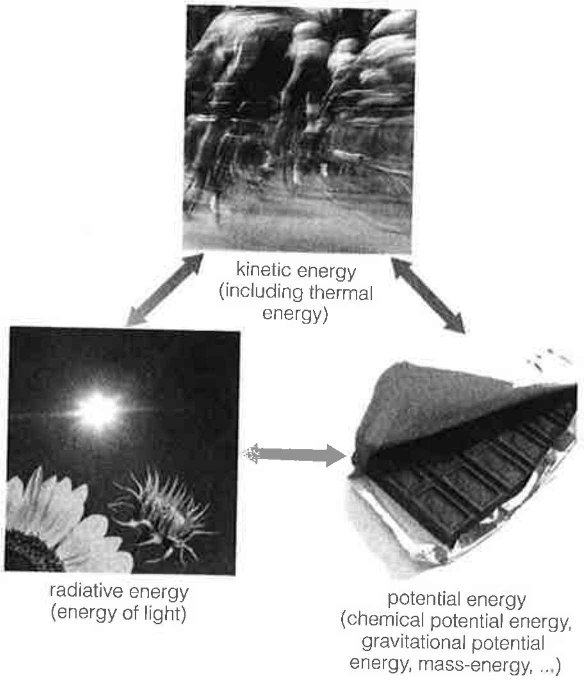
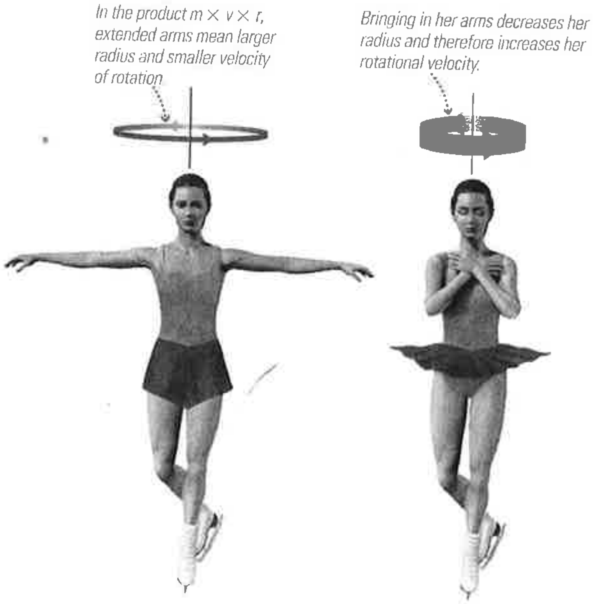


Figure 1 | The law of conservation of energy means that can be converted from one form to another, but cannot be created or destroyed.



In the product $m \times v \times r$, extended arms mean larger radius and smaller velocity of rotation

Bringing in her arms decreases her radius and therefore increases her rotational velocity.

Figure 2 | A spinning skater conserves angular momentum.

belt between Mars and Jupiter, while comets are found both in the *Kuiper belt* just beyond the orbit of Neptune and in the more distant, spherical *Oort cloud.* Our theory of solar system formation must account both for the vast numbers of small bodies and for their distribution in these three major regions.

Feature 4: Exceptions to the Rules The fourth key feature of our solar system is that there are a few notable exceptions to the general rules. For example, while most of the planets rotate in the same direction as they orbit, Uranus rotates nearly on its side and Venus rotates "backward" (opposite the direction of planetary orbits). Similarly, while most large moons orbit in their planet's equatorial plane in the same direction as their planet rotates, many small moons have inclined or backward orbits.

One of the most interesting exceptions is our own Moon. While the other terrestrial planets have either no moons (Mercury and Venus) or very tiny moons (Mars has two small moons), Earth has one of the largest moons in the solar system. Our formation theory must be able to account for such exceptions, even while it explains the general rules.

4.2 The Birth of the Solar System

The four major features of our solar system are difficult to attribute to coincidence, and in science we assume that these features have a natural explanation. In this section, we'll discuss how our modern theory of the birth of our solar system successfully explains all the major features.

What theory best explains the orderly patterns of motion in our solar system?

As we discussed briefly in Chapter 1 (see Figure 1.9), scientists now believe that star systems are born through the gravitational collapse of huge clouds of gas in space. This idea was first proposed in 1755 by the German philosopher Immanuel Kant, but it gained acceptance only much more recently, after detailed models based on this idea proved successful at explaining the major features of the solar system. The success of such models elevated the idea to the status of a scientific *theory* [Section 3.2]. We now call it the **nebular theory** of solar system formation, because an interstellar cloud is usually called a *nebula* (Latin for "cloud").

The particular cloud that gave birth to our own solar system about $4\frac{1}{2}$ billion years ago is usually called the **solar nebula.** Recall from Chapter 1 that the universe had already been around for more than 9 billion years by that time, so generations of stars had converted about 2% (by mass) of the original hydrogen and helium from the Big Bang into heavier elements. That is, the solar nebula was made up of about 98% hydrogen and helium, and only 2% everything else combined. The rocky terrestrial planets are therefore made from material that represented only a tiny fraction of the solar nebula.

Think about it Recall that the universe was born with only two chemical elements in it: hydrogen and helium. Could a solar system like ours have formed with the first generation of stars after the Big Bang? Explain.

The solar nebula probably began as a large and roughly spherical cloud of very cold, low-density gas. Initially, this gas was probably so spread out—perhaps over a region a few light-years in diameter—that gravity alone may not have been able to pull it together to start its collapse. Instead, the collapse may have been triggered by a cataclysmic event, such as the impact of a shock wave from the explosion of a nearby star (a *supernova*).

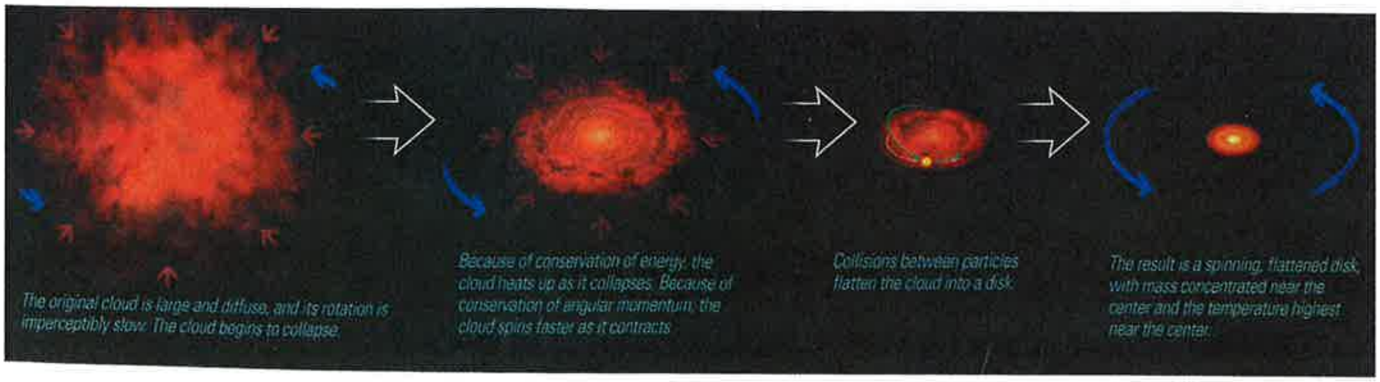
Once the collapse started, the law of gravity ensured that it would continue. Remember that the strength of gravity follows an inverse square law with distance [Section 3.3]. Because the mass of the cloud remained the same as it shrank, the strength of gravity increased as the diameter of the cloud decreased. For example, when the diameter decreased by half, the force of gravity increased by a factor of four.

Gravity pulls inward in all directions, so you might at first guess that the solar nebula would have remained spherical as it shrank. Indeed, the idea that gravity pulls in all directions explains why the Sun and the planets are spherical. However, gravity is not the only physical law that affects the collapse of a cloud of gas. As the solar nebula shrank in size, three important processes altered its density, temperature, and shape, changing it from a large spread-out cloud to a much smaller spinning disk (**Figure 4.6**):

- *Heating.* The temperature of the solar nebula increased as it collapsed. Such heating represents energy conservation in action (see Tools of Science, p. 62). As the cloud shrank, its gravitational potential energy was converted to the kinetic energy of individual gas particles falling inward. These particles crashed into one another, converting the kinetic energy of their inward fall to the random motions of thermal energy. The Sun formed in the center of the cloud, where temperatures and densities were highest.
- *Spinning.* Like an ice skater pulling in her arms as she spins, the solar nebula rotated faster and faster as it shrank in radius. This increase in rotation rate represents conservation of angular momentum in action (see Tools of Science, p. 62). The rotation of the cloud may have been imperceptibly slow before its collapse began, but over time the cloud's shrinkage made fast rotation inevitable. The rapid rotation also ensured that material in the cloud remained spread out rather than all collapsing into the center.
- *Flattening.* The solar nebula flattened into a disk. This flattening is a natural consequence of collisions between particles in a spinning cloud. A cloud may start with any size or shape, and different clumps of gas within the cloud may be moving in random directions at random speeds. These clumps collide and merge as the cloud collapses, and each new clump has the average velocity of the clumps that formed it. In this way, the random motions of the original cloud become more orderly as the cloud collapses, changing the cloud from its original lumpy shape into a rotating, flattened disk with nearly circular orbits. Note that this process conserves angular momentum, as it must: The rotating disk still has the same total angular momentum as the original cloud.

We can now see that the nebular theory successfully explains our first major feature of the solar system, which is its orderly motions. The planets all orbit the Sun in nearly the same plane because they formed in a flat disk. The direction in which the disk was spinning became the direction of the Sun's

Figure 4.6 | This sequence of illustrations shows how the gravitational collapse of a large cloud of gas causes it to become a spinning disk of matter. The hot, dense central bulge becomes a star, while planets can form in the surrounding disk.



rotation and the orbits of the planets. Computer models show that planets would have tended to rotate in this same direction as they formed—which is why most planets rotate the same way today—though the small sizes of planets compared to the entire disk allowed some exceptions to arise. The fact that collisions in the disk tended to make orbits more circular explains why most planets have nearly circular orbits.

See it for yourself You can demonstrate the development of orderly motion, much as it occurred in the solar system, by sprinkling pepper into a bowl of water and stirring it quickly in random directions. The water molecules constantly collide with one another, so the motions of the pepper grains tend to settle down into a slow rotation representing the average of the original random velocities. Try the experiment several times, stirring the water differently each time. Do the random motions ever cancel out exactly, resulting in no rotation at all? Describe what happens and how this demonstration is similar to what took place in the solar nebula.

How does our theory account for the features of planets, moons, and small bodies?

The nebular theory also accounts for the other three major features of the solar system. To see how, we must investigate what happened after the solar nebula took the shape of a spinning, flattened disk.

In the center of the disk, gravity drew together enough material to form the Sun. In the surrounding disk, however, the gaseous material was too spread out for gravity alone to clump it up. Instead, material had to begin clumping in some other way and to grow in size until gravity could start pulling it together into planets. In essence, planet formation required the presence of "seeds"—solid bits of matter around which gravity could ultimately build planets.

The basic process of seed formation was probably much like that of the formation of snowflakes in clouds on Earth: When the temperature is low enough, some atoms or molecules in a gas may bond together and solidify. The general process in which solid (or liquid) particles form in a gas is called **condensation**—we say that the particles *condense* out of the gas. Different materials condense at different temperatures. As summarized in **Table 4.3**, the ingredients of the solar nebula fell into four major categories:

- *Hydrogen and helium gas (98% of the solar nebula).* These gases never condense under the conditions present in a nebula.
- *Hydrogen compounds (1.4% of the solar nebula).* Materials such as water (H_2O), methane (CH_4), and ammonia (NH_3) can solidify into **ices** at low temperatures (below about 150 K under the low pressure of the solar nebula).
- *Rock (0.4% of the solar nebula).* Rocky material is gaseous at high temperatures, but condenses into solid form at temperatures between about 500 K and 1300 K, depending on the type of rock.
- *Metal (0.2% of the solar nebula).* Metals such as iron, nickel, and aluminum are also gaseous at very high temperatures, but condense into solid form at higher temperatures than rock—typically in the range of 1000 K to 1600 K.

Because hydrogen and helium gas made up 98% of the solar nebula's mass and did not condense, the vast majority of the nebula remained gaseous. However, other materials could condense wherever the temperature allowed (**Figure 4.7**). Close to the forming Sun, where the temperature was above 1600 K, it was too hot for any material to condense. Near what is now Mercury's orbit, the temperature was low enough for metals and some types of rock to condense into tiny solid particles, but it was far too hot for hydrogen compounds to condense into ices. Ices

Table 4.3 Materials in the Solar Nebula

A summary of the four types of materials present in the solar nebula. The squares represent the relative proportion of each type (by mass).

	Examples	Typical condensation temperature	Relative abundance (by mass)
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	■ 98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	■ 1.4%
Rock 	various minerals	500–1300 K	■ 0.4%
Metals 	iron, nickel, aluminum	1000–1600 K	■ 0.2%

could form only beyond the **frost line,** which lay between the present-day orbits of Mars and Jupiter. The frost line therefore marked the key transition between the warm inner region of the solar system where terrestrial planets formed and the cool outer region where jovian planets formed.

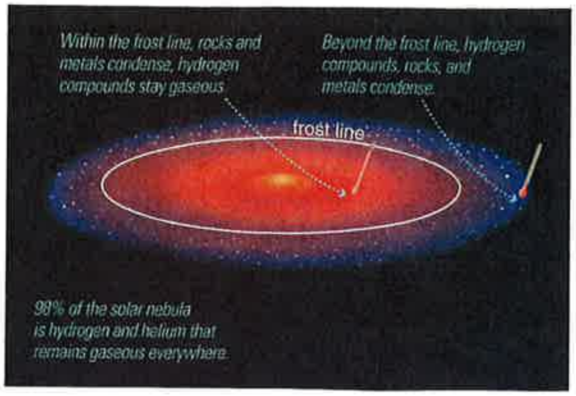


Figure 4.7 | Temperature differences in the solar nebula led to different kinds of condensed materials at different distances from the Sun.

Think about it

Consider a region of the solar nebula in which the temperature was about 1300 K. Based on the data in Table 4.3, what fraction of the material in this region was gaseous? What were the solid particles in this region made of? Answer the same questions for a region with a temperature of 100 K. Would the 100 K region be closer to or farther from the Sun than the 1300 K region? Explain.

The first particles to condense were microscopic in size and orbited the Sun with the same orderly, circular paths as the gas from which they condensed. Individual particles therefore moved at nearly the same speed as neighboring particles, so "collisions" were more like gentle touches. Under these circumstances, particles could stick together through electrostatic forces—the same static electricity that makes hair stick to a comb. Small particles thereby began to combine into larger ones. As the particles grew in mass, gravity began to aid the process of their sticking together, accelerating their growth. The general process by which particles stick together and grow larger is called **accretion.** We refer to particles that grew to the size of boulders or larger as **planetesimals,** which means "pieces of planets."

Explaining the Two Types of Planets We can use the processes of condensation and accretion to explain why the solar system ended up with two types of planets. In the inner solar system, where only metal and rock could condense into solid particles, the planetesimals ended up being made of metal and rock. These planetesimals grew rapidly at first, with some probably reaching hundreds of kilometers in size in only a few million years—a long time in human terms, but only about 1/1000 the present age of the solar system.

Further growth became more difficult once the planetesimals reached these relatively large sizes. Gravitational encounters between planetesimals tended to alter their orbits, particularly those of the smaller planetesimals. With different orbits crossing each other, collisions between planetesimals occurred at higher speeds and hence became more destructive. Such collisions produced fragmentation more often than accretion. Only the largest planetesimals avoided being shattered and grew into full-fledged planets. **Figure 4.8** summarizes how the terrestrial planets were built from the solid bits of metal and rock that condensed in the inner solar system.

The planet formation process began similarly in the outer solar system, except the lower temperatures beyond the frost line meant that ices condensed along with metal and rock. Because ices were more abundant than rock and metal (see Table 4.3), the icy planetesimals in the outer solar system grew to larger sizes than the rocky planetesimals of the inner solar system. According to the leading model of jovian planet formation, some of the icy planetesimals grew to masses many times that of Earth. With these large masses, their gravity became strong enough to capture and hold some of the hydrogen and helium gas that made up the vast majority of the surrounding solar nebula. As the growing planets accumulated gas, their gravity grew stronger still, allowing them to capture even more gas. Ultimately, the jovian planets grew so much that they bore little resemblance to the icy seeds from which they started.

This model also explains most of the large moons of the jovian planets. The same processes of heating, spinning, and flattening that made the disk of the solar nebula should also have affected the gas drawn by gravity to the young jovian planets. Each jovian planet came to be

Common Misconceptions

SOLAR GRAVITY AND THE DENSITY OF PLANETS

Some people guess that it was the Sun's gravity that pulled the dense rocky and metallic materials to the inner part of the solar nebula, or that gases escaped from the inner nebula because gravity couldn't hold them. But this is not the case—all the ingredients were orbiting the Sun together under the influence of the Sun's gravity. The orbit of a particle or a planet does not depend on its size or density, so the Sun's gravity cannot be the cause of the different types of planets. Rather, the different temperatures in the solar nebula explain why we have terrestrial and jovian planets.

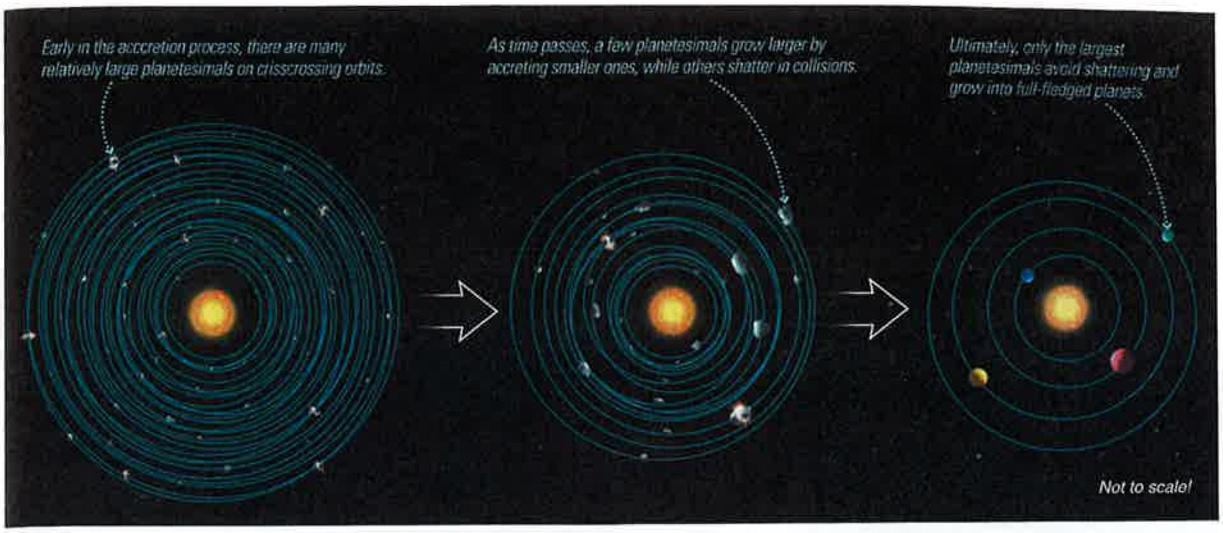


Figure 4.8 | These diagrams show how planetesimals made of metal and rock gradually accreted to make the terrestrial planets.

surrounded by its own disk of gas, spinning in the same direction as the planet rotated (**Figure 4.9**). Moons that accreted from icy planetesimals within these disks therefore ended up with nearly circular orbits going in the same direction as their planet's rotation and lying close to their planet's equatorial plane.

One key question remains for us to answer: Given that the vast majority of the hydrogen and helium gas in the solar nebula never became part of any planet, what happened to it? Models and observations of other star systems suggest that it was cleared away by a combination of energetic light from the young Sun and the *solar wind*—a stream of charged particles continually blown outward in all directions from the Sun [Section 8.1]. The compositions of the planets have remained nearly the same since this gas cleared. If the gas had remained longer, it might have continued to cool until hydrogen compounds condensed into ices even in the inner solar system. In that case, the terrestrial planets might have accreted abundant ice, and perhaps some hydrogen and helium gas as well, changing their basic nature. At the other extreme, if the gas had been blown out much earlier, the raw materials of the planets might have been swept away before the planets could fully form. Although these extreme scenarios did not occur in our solar system, they may sometimes occur around other stars.

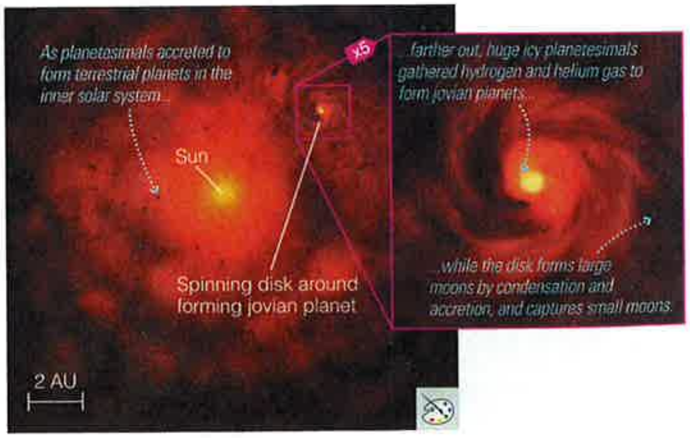


Figure 4.9 | The jovian planets grew as large icy planetesimals captured hydrogen and helium gas from the solar nebula and became surrounded by spinning disks of gas as they formed, much like the disk of the entire solar nebula but smaller in size. This painting shows the gas and planetesimals surrounding one jovian planet in the larger solar nebula.

Explaining Asteroids and Comets

You can probably already see how the nebular theory accounts for the existence of so many asteroids and comets: They are simply "leftover" planetesimals from the era of planet formation. Asteroids are the leftover rocky planetesimals of the inner solar system, while comets are the leftover icy planetesimals of the outer solar system.

The asteroids and comets that exist today probably represent only a small fraction of the leftover planetesimals that roamed the young solar system. Most of the rest must have collided with planets or moons. On worlds with solid surfaces, we see the evidence of past collisions as *impact craters*. Careful study of impact craters on the Moon shows that the vast majority of these collisions occurred in the first few hundred million years of our solar system's history, during the period we call the **heavy bombardment**. Every world in our solar system must have been pelted by impacts during the heavy bombardment (**Figure 4.10**), and most of the craters we see on the Moon and other worlds date from this period.

Figure 4.10 | Around 4 billion years ago, Earth, its Moon, and the other planets were heavily bombarded by leftover planetesimals. This painting shows the young Earth and Moon, with an impact in progress on Earth.

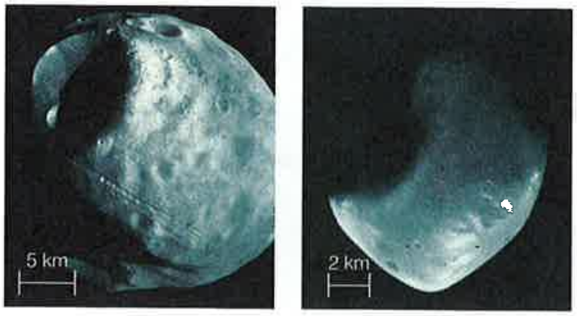
The impacts of the heavy bombardment did more than just batter the planets. They also brought materials from other regions of the solar system—a fact that is critical to our existence on Earth today. Recall that the terrestrial planets were built from planetesimals made of metal and rock. These planetesimals probably contained little or no water or other hydrogen compounds, because it was too hot for these compounds to condense in our region of the solar nebula. How, then, did Earth come to have the water that makes up our oceans and the gases that first formed our atmosphere? The likely answer is that water, along with other hydrogen compounds, was brought to Earth and other terrestrial planets during their formation by the impacts of water-bearing planetesimals that formed farther from the Sun. Remarkably, the water we drink and the air we breathe probably once were part of planetesimals that accreted beyond the orbit of Mars.

The collisions of the heavy bombardment also explain why asteroids and comets are today found in the distinct regions of the asteroid belt, Kuiper belt, and Oort cloud. Jupiter's gravity stirred up the orbits of leftover planetesimals in the inner solar system, ultimately leaving asteroids concentrated in the asteroid belt. The Kuiper belt represents leftover planetesimals that formed beyond Neptune, where there were no large planets to collide with. The Oort cloud is thought to contain comets that formed in the region between the jovian planets but were "kicked out" to their current great distances when they passed by one of the jovian planets and the planet's gravity accelerated them to high speed in random directions. Once they were far from the Sun, gravitational nudges from other stars further randomized their orbits.

Explaining the Exceptions We have now explained all the major features of our solar system except the "exceptions to the rules." Today, we think that most of these exceptions arose from collisions and other processes that involved the leftover planetesimals in the young solar system.

Let's start with unusual moons. We have explained the orbits of most large jovian planet moons by their formation in a disk that swirled around the forming planet. But how do we explain moons with unusual orbits, such as those that go in the "wrong" direction (opposite their planet's rotation) or that have large inclinations to their planet's equator? These moons are probably leftover planetesimals that originally orbited the Sun but were then captured into planetary orbit.

It's not easy for a planet to capture a moon, because the law of gravity dictates that a small object passing a large planet will simply fly on by. An object can be captured only if it loses enough orbital energy to settle into a circular or elliptical orbit. For the jovian planets, this type of capture could have occurred when the planets were very young and still surrounded by an extended cloud of relatively dense gas. A passing planetesimal would have been slowed by friction with this gas, and if it was slowed enough, it could have become an orbiting moon. This process is more likely with smaller objects, explaining why most of the jovian moons are only a few kilometers across. Moreover, because of the random nature of the capture process, captured moons would not necessarily orbit in the same direction as their planet or in its equatorial plane—and this is the case for most of the small jovian moons. Mars may also have captured its two small moons, Phobos and Deimos, at a time when it had a much more extended atmosphere than it does today (**Figure 4.11**).

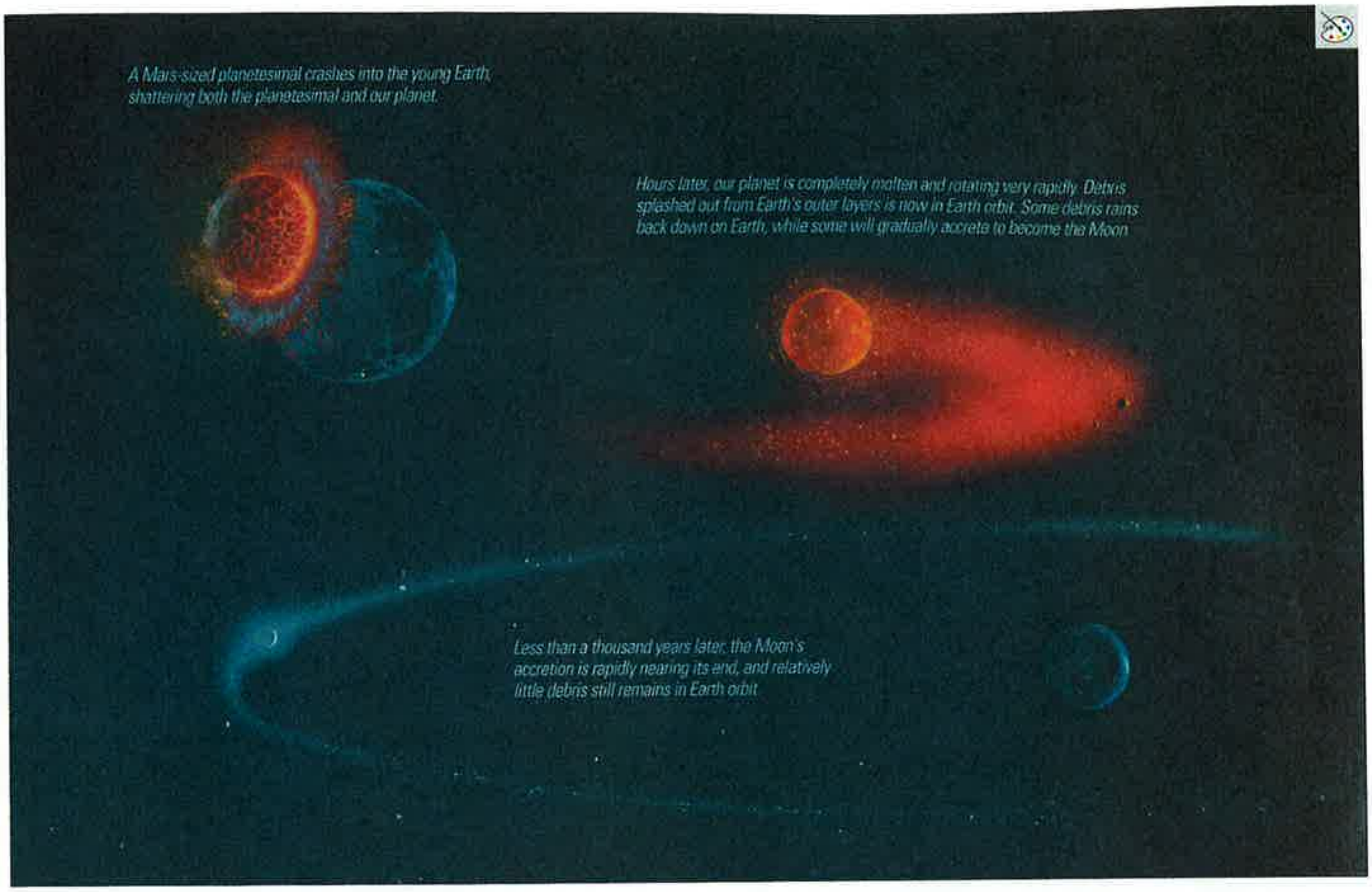


a Phobos

b Deimos

Figure 4.11 | The two moons of Mars are probably captured asteroids. Phobos is only about 13 kilometers across and Deimos is only about 8 kilometers across—making each of these two moons small enough to fit within the boundaries of a typical large city.

Capture processes cannot explain our own Moon, however, because it is much too large to have been captured by a small planet like Earth. We can also rule out the possibility that our Moon formed simultaneously with Earth: If both had formed together, they would have accreted from planetesimals of the same type and have approximately the same composition and density, but that is not the case. The Moon's density is considerably lower than Earth's, indicating that it has a very different average composition.



A Mars-sized planetesimal crashes into the young Earth, shattering both the planetesimal and our planet.

Hours later, our planet is completely molten and rotating very rapidly. Debris splashed out from Earth's outer layers is now in Earth orbit. Some debris rains back down on Earth, while some will gradually accrete to become the Moon

Less than a thousand years later, the Moon's accretion is rapidly nearing its end, and relatively little debris still remains in Earth orbit

Figure 4.12 | Artist's conception of the giant impact hypothesis for the formation of our Moon. As shown, the Moon formed quite close to a rapidly rotating Earth, but over billions of years tidal forces have slowed Earth's rotation and moved the Moon's orbit outward.

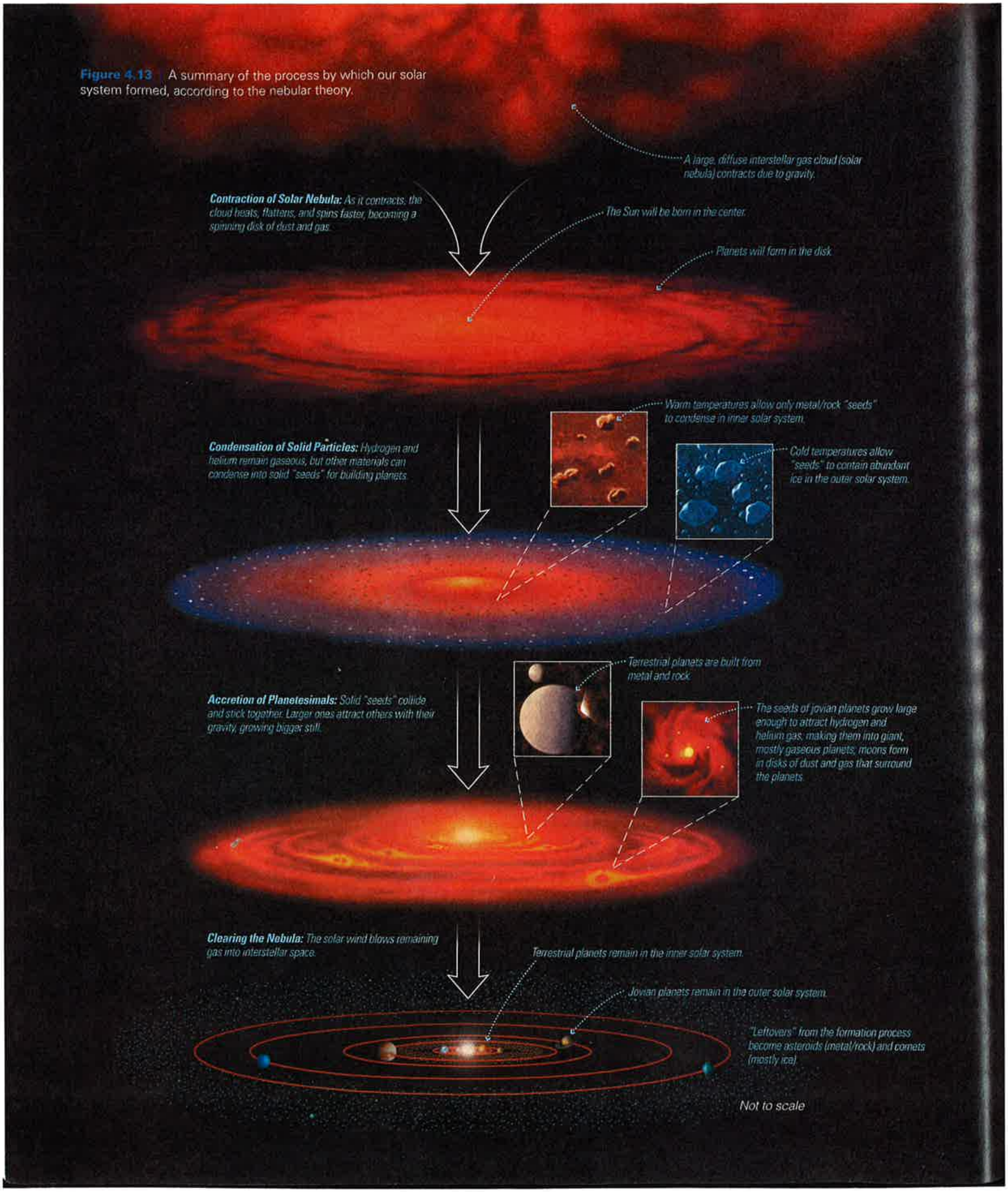
So how did we get our Moon? Today, the leading hypothesis suggests that it formed as the result of a **giant impact** between Earth and a huge planetesimal.

According to models, a few leftover planetesimals may have been as large as Mars. If one of these Mars-size objects struck a young planet, the blow might have tilted the planet's axis, changed the planet's rotation rate, or completely shattered the planet. The giant impact hypothesis holds that a Mars-size object hit Earth at a speed and angle that blasted Earth's outer layers into space. According to computer simulations, this material could have collected into orbit around our planet, and accretion within this ring of debris could have formed the Moon (**Figure 4.12**).

Strong support for the giant impact hypothesis comes from two features of the Moon's composition. First, the Moon's overall composition is quite similar to that of Earth's outer layers—just as we should expect if it were made from material blasted away from those layers. Second, the Moon has a much smaller proportion of easily vaporized ingredients (such as water) than Earth. This fact supports the hypothesis because the heat of the impact would have vaporized these ingredients. As gases, they would not have participated in the process of accretion that formed the Moon, since only solid material could have participated in this accretion.

Giant impacts may also explain other exceptions. Mercury's surprisingly high density may be the result of a giant impact that blasted away its outer, lower density layers. Giant impacts might also have been responsible for tilting the axes of planets (including Earth), for tipping Uranus on its side, and perhaps for Venus's slow and backward rotation.

Figure 4.13 A summary of the process by which our solar system formed, according to the nebular theory.



A large, diffuse interstellar gas cloud (solar nebula) contracts due to gravity.

Contraction of Solar Nebula: As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas.

The Sun will be born in the center.

Planets will form in the disk.

Warm temperatures allow only metal/rock "seeds" to condense in inner solar system.

Condensation of Solid Particles: Hydrogen and helium remain gaseous, but other materials can condense into solid "seeds" for building planets.

Cold temperatures allow "seeds" to contain abundant ice in the outer solar system.

Terrestrial planets are built from metal and rock.

Accretion of Planetesimals: Solid "seeds" collide and stick together. Larger ones attract others with their gravity, growing bigger still.

The seeds of jovian planets grow large enough to attract hydrogen and helium gas, making them into giant, mostly gaseous planets; moons form in disks of dust and gas that surround the planets.

Clearing the Nebula: The solar wind blows remaining gas into interstellar space.

Terrestrial planets remain in the inner solar system.

Jovian planets remain in the outer solar system.

"Leftovers" from the formation process become asteroids (metal/rock) and comets (mostly ice).

Not to scale

Although we cannot definitively explain these exceptions to the general rules, the main point is clear: The chaotic processes that accompanied planet formation, including the many collisions that surely occurred, are *expected* to have caused at least a few exceptions.

Summary We have found that detailed models based on the nebular theory successfully explain all the major features of our solar system. That is why scientists are confident that the theory captures the essence of what actually happened, even though we may not yet know all the details. **Figure 4.13** summarizes the formation of our solar system according to the nebular theory.

THE PROCESS OF SCIENCE IN ACTION

4.3 The Age of the Solar System

We've said that the solar system formed about $4\frac{1}{2}$ billion years ago. But since no one was around when the solar system was born, how can we possibly know how old it is? The answer is that careful observations and experiments enable scientists to measure the ages of things much older than we are. For example, we can measure ages of trees up to a few thousand years old by counting tree rings, and we can study Earth's climate over a period of a few hundred thousand years by drilling deep into the ice sheets of Greenland and Antarctica, where we see distinct layers laid down each year. To study things that are millions or billions of years old, we must determine the ages of rocks. The technique scientists use to measure these enormous ages is the focus of this chapter's case study in the process of science in action.

How do we determine the age of Earth and the solar system?

The most reliable method for measuring the age of a rock is **radiometric dating,** which relies on careful measurement of the proportions of various atoms in the rock. The method works because some atoms undergo changes with time that allow us to determine how long they have been held in place within the rock's solid structure.

Isotopes and Radioactive Decay You may recall from high school that each chemical element is uniquely characterized by the number of protons in its nucleus. Different **isotopes** of the same element differ only in their number of neutrons. For example, any atom with 6 protons in its nucleus is an atom of carbon, but carbon atoms come in three different isotopes (**Figure 4.14**): carbon-12, which has 6 neutrons in addition to the 6 protons; carbon-13, which has 7 neutrons; and carbon-14, which has 8 neutrons.

Most of the atoms and isotopes we encounter in daily life are stable, meaning that their nuclei stay the same at all times. For example, most of the carbon in our bodies is carbon-12, which is stable. But some isotopes are unstable, meaning that their nuclei are prone to spontaneous change, or *decay,* such as breaking apart or having a proton turn into a neutron. These unstable nuclei are said to be **radioactive.** Carbon-14 is an example of a radioactive isotope, because it undergoes spontaneous change that turns it into nitrogen-14.

Radioactive decay always occurs at the same rate for any particular radioactive isotope, and scientists can measure these rates in the laboratory. We generally characterize the decay rate of an element by stating its **half-life**—the length of time it would take for half its nuclei to decay. Note that it takes only a few months to years of laboratory measurements to pin down the decay rate and determine the half-life, even if the half-life is billions of years. The half-life of carbon-14 is about 5700 years, which makes it useful to archaeologists trying

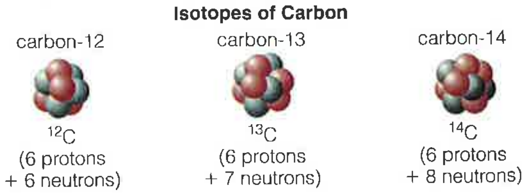


Figure 4.14 | Different isotopes of a chemical element contain the same number of protons, but different numbers of neutrons.

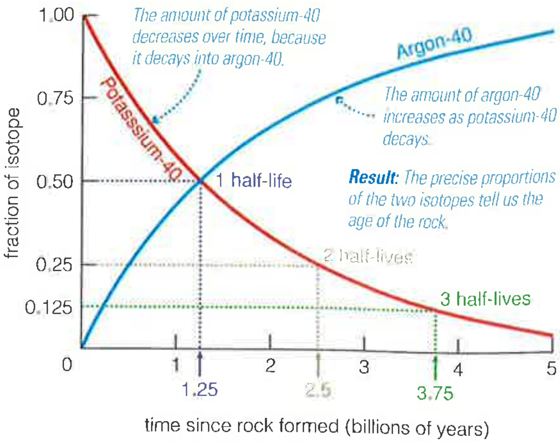


Figure 4.15 | Potassium-40 is radioactive, decaying into argon-40 with a half-life of 1.25 billion years. The red curve shows the decreasing amount of potassium-40, and the blue curve shows the increasing amount of argon-40. The amount of potassium-40 remaining drops in half with each successive half-life.

to determine the dates of ancient human settlements, but which is far too short for dating rocks that are millions or billions of years old. To see how dating of rocks works, let's consider decay of the radioactive isotope potassium-40 into argon-40, a process with a half-life of 1.25 billion years. (Potassium-40 also decays by other paths, but we focus only on decay into argon-40 to keep the discussion simple.)

Radiometric Dating Consider a small piece of rock that contained 1 microgram of potassium-40 and no argon-40 when it formed (solidified) long ago. The half-life of 1.25 billion years means that half the original potassium-40 would have decayed into argon-40 by the time the rock was 1.25 billion years old, so at that time the rock would contain $\frac{1}{2}$ microgram of potassium-40 and $\frac{1}{2}$ microgram of argon-40. Half of this remaining potassium-40 would then have decayed by the end of the next 1.25 billion years, so after 2.5 billion years the rock would contain $\frac{1}{4}$ microgram of potassium-40 and $\frac{3}{4}$ microgram of argon-40. After three half-lives, or 3.75 billion years, only $\frac{1}{8}$ microgram of potassium-40 would remain, while $\frac{7}{8}$ microgram would have become argon-40. **Figure 4.15** summarizes the gradual decrease in the amount of potassium-40 and corresponding rise in the amount of argon-40.

We can now see the essence of radiometric dating. Suppose you find a rock that contains equal numbers of atoms of potassium-40 and argon-40. If you assume that all the argon came from potassium decay (and if the rock shows no evidence of subsequent heating that could have allowed any argon to escape), then it must have taken precisely one half-life for the rock to end up with equal amounts of the two isotopes. You can therefore conclude that the rock is 1.25 billion years old. The only question is whether you are right in assuming that the rock lacked argon-40 when it formed. In this case, knowing a bit of "rock chemistry" helps. Potassium-40 is a natural ingredient of many minerals in rocks, but argon-40 is a gas that does not combine with other elements and did not condense in the solar nebula. If you find argon-40 gas trapped inside minerals, it must have come from radioactive decay of potassium-40.

Radiometric dating is possible with many other radioactive isotopes as well. In many cases, we can date a rock that contains more than one radioactive isotope; agreement between the ages calculated from the different isotopes gives us confidence that we have dated the rock correctly. We can also sometimes check results from radiometric dating against other methods of measuring ages. For example, some fairly recent archaeological artifacts have dates printed on them, and the dates agree with ages found by radiometric dating. We can validate the $4\frac{1}{2}$-billion-year radiometric age for the solar system as a whole by comparing it to an age based on detailed study of the Sun. Theoretical models of the Sun, along with observations of other stars, show that stars slowly expand and brighten as they age. The model ages are not nearly as precise as radiometric ages, but they confirm that the Sun is between about 4 and 5 billion years old. Overall, the technique of radiometric dating has been checked in so many ways and relies on such basic scientific principles that there is no longer any serious scientific debate about its validity.

Ages of Earth Rocks, Moon Rocks, and Meteorites Radiometric dating allows us to determine the length of time that has passed since the atoms in a rock became locked together in their present arrangement, which in most cases means the time *since the rock last solidified*. The ages of rocks therefore vary greatly. Some Earth rocks are quite young because they formed recently from molten lava, and other Earth rocks have a great variety of ages because they melted and then re-solidified at different times in Earth's history. The oldest Earth rocks are over 4 billion years old, and some small mineral grains date to nearly 4.4 billion years ago. Earth as a whole must be even older than these oldest rocks and minerals.

Moon rocks brought back by the Apollo astronauts date to as far back as 4.4 billion years ago. Although they are older than Earth rocks, these Moon rocks must still be younger than the Moon itself. The ages of these rocks also tell us that the giant impact thought to have created the Moon must have occurred more than 4.4 billion years ago.

To go all the way back to the origin of the solar system, we must find rocks that have not melted or vaporized since they first condensed in the solar nebula. Meteorites that have fallen to Earth are our source of such rocks. Many meteorites appear to have remained unchanged since they condensed and accreted in the early solar system. Careful analysis of radioactive isotopes in meteorites shows that the oldest ones formed about 4.55 billion years ago, so this time must mark the beginning of accretion in the solar nebula. Because the planets accreted within a few tens of millions of years, Earth and the other planets must have finished forming about 4.5 billion years ago.

The Bottom Line In science, we often want to know the ages of things that are far older than we are. Scientists have therefore developed techniques that in many cases can date extremely old objects with amazing precision. Radiometric dating is one of the most important techniques, and it is also one of the best tested and verified. As a result, we have great confidence in ages established by radiometric dating, including the age of Earth and our solar system.

Summary of Key Concepts

4.1 Characteristics of the Solar System

What does the solar system look like?

Our solar system consists of the Sun, the planets and their moons, and vast numbers of asteroids and comets. The planets are tiny compared to the distances between them. Each world has its own unique character, but there are many clear patterns among the worlds.

What features of our solar system provide clues to how it formed?

Four major features provide clues: (1) The Sun, planets, and large moons generally rotate and orbit in a very organized way. (2) The planets divide clearly into two groups: **terrestrial** and **jovian.** (3) The solar system contains huge numbers of asteroids and comets. (4) There are some notable exceptions to these general patterns.

4.2 The Birth of the Solar System

What theory best explains the orderly patterns of motion in our solar system?

The **nebular theory** holds that the solar system formed from the gravitational collapse of a great cloud of gas and dust. As the **solar nebula** shrank in size, it got hotter, spun faster, and flattened out. The orderly motions we observe today came from the orderly motion of this spinning disk.

How does our theory account for the features of planets, moons, and small bodies?

Planets formed around solid "seeds" of matter that condensed from gas and then grew through **accretion.** In the inner solar system, high temperatures allowed only metal and rock to condense, which explains why terrestrial worlds are made of metal and rock. In the outer solar system, cold temperatures allowed more abundant ices to condense along with metal and rock, making some **planetesimals** that grew large enough for their gravity to draw in hydrogen and helium gas, building massive jovian planets. **Asteroids** are the rocky leftover planetesimals of the inner solar system, and **comets** are the icy leftover planetesimals of the outer solar system. Most of the exceptions to the general trends probably arose from collisions or close encounters with leftover planetesimals. Our Moon probably resulted from a **giant impact** between a Mars-size planetesimal and the young Earth.

✻ THE PROCESS OF SCIENCE IN ACTION

4.3 The Age of the Solar System

How do we determine the age of Earth and the solar system?

The technique of **radiometric dating** allows us to determine the age of a rock by carefully measuring its proportions of a radioactive isotope and the decay product of that isotope. We determine the age of Earth and the solar system by measuring the ages of the oldest meteorites, which are about 4.55 billion years old.

Investigations

Quick Quiz

Choose the best answer to each of the following; answers are in Appendix D. Explain your reasoning with one or more complete sentences.

1. How might our solar system be different if the frost line were much farther out? (a) Earth would be smaller. (b) Jupiter would not exist. (c) It would be no different.
2. Which of the following kinds of object resides closest to the Sun on average? (a) comets (b) asteroids (c) jovian planets
3. Planetary orbits are (a) very eccentric (stretched out) ellipses and in the same plane. (b) fairly circular and in the same plane. (c) fairly circular but oriented in random directions.
4. How many of the planets orbit the Sun in the same direction that Earth does? (a) a few (b) most (c) all
5. Which have more moons on average? (a) jovian planets (b) terrestrial planets (c) Terrestrial and jovian planets both have about the same number of moons.
6. Which ingredients made up about 98% of the solar nebula? (a) rock and metal (b) hydrogen compounds (c) hydrogen and helium
7. In which list are the major steps of solar system formation in the correct order? (a) gravitational collapse of the solar nebula, accretion, condensation (b) gravitational collapse of the solar nebula, condensation, accretion (c) accretion, condensation, gravitational collapse of the solar nebula
8. Which of the following changes did *not* occur during the collapse of the solar nebula? (a) spinning faster (b) heating up (c) concentrating denser materials nearer the Sun
9. Leftover ice-rich planetesimals are called (a) comets. (b) asteroids. (c) meteors.
10. Why didn't a terrestrial planet form at the location of the asteroid belt? (a) There was never enough material in that part of the solar nebula. (b) The solar wind cleared away nebular material there. (c) Jupiter's gravity kept planetesimals from accreting into a planet there.
11. What's the leading theory for the origin of the Moon? (a) It formed at the same time as Earth. (b) It formed from the material ejected by a giant impact on Earth. (c) It split off from a rapidly rotating Earth.
12. About how old is the solar system? (a) 4.5 million years (b) 4.5 billion years (c) 4.5 trillion years

Short-Answer/Essay Questions

Explain all answers clearly, with complete sentences and proper essay structure, if needed. An asterisk (*) designates a quantitative problem, for which you should show all your work.

13. *Planetary Tour.* Based on the brief planetary tour in this chapter, which planet besides Earth do you think is the most interesting, and why? Defend your opinion clearly in two or three paragraphs.
14. *Patterns of Motion.* In one or two paragraphs, summarize the orderly patterns of motion in our solar system and explain why they suggest that the Sun and the planets all formed at one time from one cloud of gas, rather than as individual objects at different times.
15. *Solar System Trends.* Use Table 4.1 to answer each of the following.
    a. Describe the relationship between distance from the Sun and surface temperature. Why does this relationship exist? Explain any notable exceptions to the trend.
    b. Describe in general how the columns for density, composition, and distance from the Sun support the classification of planets into the two categories of terrestrial and jovian.
    c. Describe the relationship between orbital period and distance from the Sun, and explain it in terms of Kepler's third law.
    d. Which column of data would you use to find out which planet has the shortest days? Do you see any notable differences in the length of a day for the different types of planets? Explain.
    e. Which planets would you expect to have seasons? Why?
16. *Two Kinds of Planets.* In words a friend would understand, explain why the jovian planets differ from the terrestrial planets in each of the following aspects: composition, size, density, distance from the Sun, and number of moons.
17. *Pluto.* How does the nebular theory explain the origin of objects like Pluto? How was its formation similar to the formation of jovian and terrestrial planets, and how was it different?
18. *An Early Solar Wind.* Suppose the solar wind had cleared away the solar nebula before the seeds of the jovian planets could gravitationally draw in hydrogen and helium gas. How would the planets of the outer solar system be different? Would they still have many moons? Explain your answer in a few sentences.
19. *History of the Elements.* Our bodies (and most living things) are made mostly of water (H_2O), which contains both hydrogen and oxygen. Summarize the history of a typical hydrogen atom from its creation to the formation of Earth. Do the same for a typical oxygen atom. (*Hint:* Review Chapter 1 to see which elements were created in the Big Bang and where the others were created.)
20. *Understanding Radiometric Dating.* Imagine you had the good fortune to find a rocky meteorite in your backyard. How would you expect its ratio of potassium-40 and argon-40 to be different from that of other rocks in your yard? Explain your answer in a few sentences.

*21. *Mission to Pluto.* The *New Horizons* spacecraft will take about 9 years to travel from Earth to Pluto. About how fast is it traveling on average? Assume that its trajectory is close to a straight line. Give your answer in AU per year and kilometers per hour.

*22. *Size Comparisons.* How many Earths could fit inside Jupiter (assuming you could fill up its total volume)? How many Jupiters could fit inside the Sun? (*Hint:* The equation for the volume of a sphere is $V = \frac{4}{3}\pi r^3$.)

*23. *Radiometric Dating.* For each of the following, assume all the argon-40 comes from radioactive decay of potassium-40, a process with a half-life of 1.25 billion years.
    a. You find a rock that contains equal amounts of potassium-40 and argon-40. How old is it? Explain.
    b. You find a rock that contains three times as much argon-40 as potassium-40. How old is it? Explain.