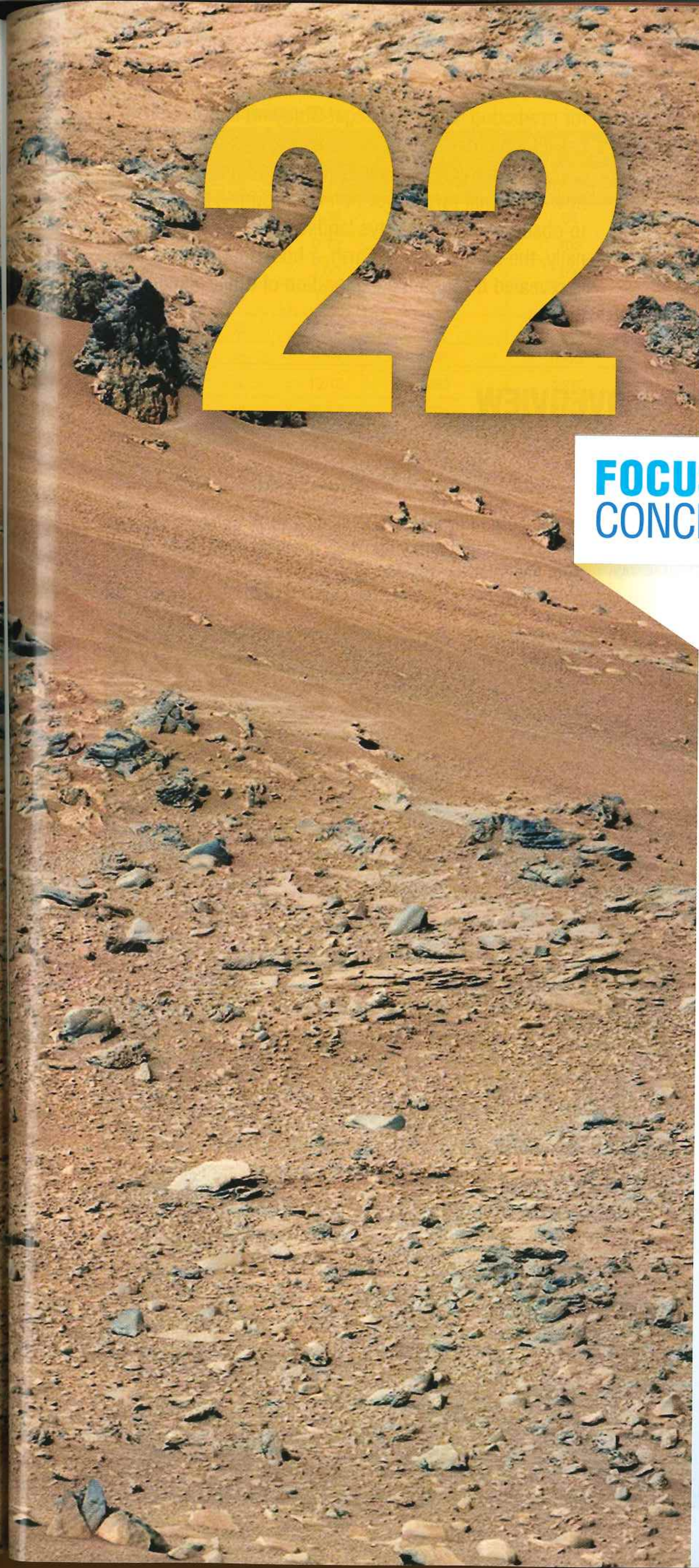


22

Touring Our Solar System[1]

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

22.1 Describe the formation of the solar system according to the nebular theory. Compare and contrast the terrestrial and Jovian planets.

22.2 List and describe the major features of Earth's Moon and explain how maria basins were produced.

22.3 Outline the principal characteristics of Mercury, Venus, and Mars. Describe their similarities to and differences from Earth.

22.4 Compare and contrast the four Jovian planets.

22.5 List and describe the principal characteristics of the small bodies that inhabit the solar system.

View of the windblown Martian surface obtained by the NASA rover *Curiosity*. The black-colored rocks are volcanic and have a composition similar to that of the rock basalt found on the Hawaiian islands. (Photo courtesy of NASA/JPL-Caltech/MSSS)

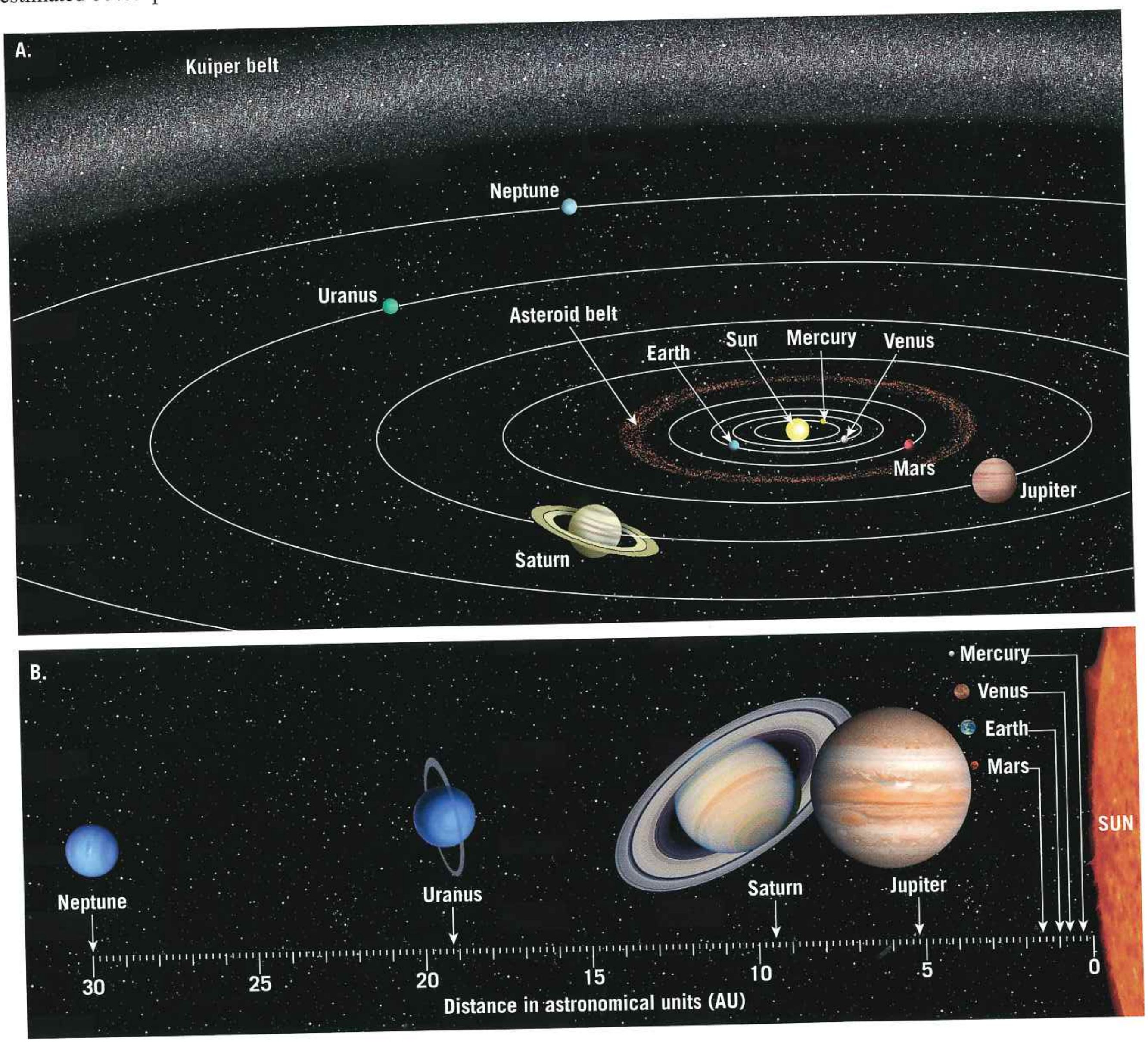
[1]This chapter was revised with the assistance of Professors Teresa Tarbuck and Mark Watry.

Planetary geology is the study of the formation and evolution of the bodies in our solar system—including the eight planets and myriad smaller objects: moons, dwarf planets, asteroids, comets, and meteoroids. Studying these objects provides valuable insights into the dynamic processes that operate on Earth. Understanding how other atmospheres evolve helps scientists build better models for predicting climate change. Studying tectonic processes on other planets helps us appreciate how these complex interactions alter Earth. In addition, seeing how erosional forces work on other bodies allows us to observe the many ways landscapes are created. Finally, the uniqueness of Earth, a body that harbors life, is revealed through the exploration of other planetary bodies.

22.1 OUR SOLAR SYSTEM: AN OVERVIEW

Describe the formation of the solar system according to the nebular theory. Compare and contrast the terrestrial and Jovian planets.

The Sun is at the center of a revolving system, trillions of miles wide, consisting of eight planets, their satellites, and numerous smaller asteroids, comets, and meteoroids. An estimated 99.85 percent of the mass of our solar system is contained within the Sun. Collectively, the planets account for most of the remaining 0.15 percent. Starting from the Sun, the planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune (**FIGURE 22.1**). Pluto was



SmartFigure 22.1 Orbits of the Planets **A.** Artistic view of the solar system, in which planets are not drawn to scale. **B.** Positions of the planets shown to scale using astronomical units (AU), where 1 AU is equal to the average distance from Earth to the Sun—150 million kilometers (93 million miles).

TABLE 22.1 Planetary Data

			Mean Distance from Sun				Orbital Velocity	
Planet	Symbol	AU*	Millions of Miles	Millions of Kilometers	Period of Revolution	Inclination of Orbit	mi/s	km/s
Mercury	☿	0.39	36	58	88^d	7°00′	29.5	47.5
Venus	♀	0.72	67	108	225^d	3°24′	21.8	35.0
Earth	⊕	1.00	93	150	365.25^d	0°00′	18.5	29.8
Mars	♂	1.52	142	228	687^d	1°51′	14.9	24.1
Jupiter	♃	5.20	483	778	12^{yr}	1°18′	8.1	13.1
Saturn	♄	9.54	886	1427	30^{yr}	2°29′	6.0	9.6
Uranus	⛢	19.18	1783	2870	84^{yr}	0°46′	4.2	6.8
Neptune	♆	30.06	2794	4497	165^{yr}	1°46′	3.3	5.3

		Diameter						
Planet	Period of Rotation	Miles	Kilometers	Relative Mass (Earth = 1)	Average Density (g/cm^3)	Polar Flattening (%)	Eccentricity†	Number of Known Satellites††
Mercury	59^d	3015	4878	0.06	5.4	0.0	0.206	0
Venus	243^d	7526	12,104	0.82	5.2	0.0	0.007	0
Earth	$23^h56^m04^s$	7920	12,756	1.00	5.5	0.3	0.017	1
Mars	$24^h37^m23^s$	4216	6794	0.11	3.9	0.5	0.093	2
Jupiter	9^h56^m	88,700	143,884	317.87	1.3	6.7	0.048	67
Saturn	10^h30^m	75,000	120,536	95.14	0.7	10.4	0.056	62
Uranus	17^h14^m	29,000	51,118	14.56	1.2	2.3	0.047	27
Neptune	16^h07^m	28,900	50,530	17.21	1.7	1.8	0.009	13

*AU = astronomical unit, Earth's mean distance from the Sun.

†Eccentricity is a measure of the amount an orbit deviates from a circular shape. The larger the number, the less circular the orbit.

††Includes all satellites discovered as of December 2012.

recently reclassified as a member of a new class of solar system bodies called *dwarf planets.*

Tethered to the Sun by gravity, all the planets travel in the same direction, on slightly elliptical orbits (**TABLE 22.1**). Gravity causes objects nearest the Sun to travel fastest. Therefore, Mercury has the highest orbital velocity, 48 kilometers (30 miles) per second, and the shortest period of revolution around the Sun, 88 Earth-days. By contrast, the distant dwarf planet Pluto has an orbital speed of just 5 kilometers (3 miles) per second and requires 248 Earth-years to complete one revolution. Most large bodies orbit the Sun approximately in the same plane. The planets' inclination with respect to the Earth–Sun orbital plane, known as the *ecliptic*, is shown in Table 22.1.

Nebular Theory: Formation of the Solar System

The **nebular theory**, which explains the formation of the solar system, proposes that the Sun and planets formed from a rotating cloud of interstellar gases (mainly hydrogen and helium) and dust called the **solar nebula**. As the solar nebula contracted due to gravity, most of the material collected in the center to form the hot *protosun*. The remaining materials formed a thick, flattened, rotating disk, within which matter gradually cooled and condensed into grains and clumps of icy, rocky material. Repeated collisions resulted in most of the material clumping together into larger and larger chunks that eventually became asteroid-sized objects called **planetesimals**.

The composition of planetesimals was largely determined by their proximity to the protosun. As you might expect, temperatures were highest in the inner solar system and decreased toward the outer edge of the disk. Therefore, between the present orbits of Mercury and Mars, the planetesimals were composed of materials with high melting temperatures—metals and rocky substances. Then, through repeated collisions and accretion, these asteroid-sized rocky bodies combined to form the four **protoplanets** that eventually became Mercury, Venus, Earth, and Mars.

The planetesimals that formed beyond the orbit of Mars, where temperatures were low, contained high percentages of ices—water, carbon dioxide, ammonia, and methane—as well as small amounts of rocky and metallic debris. It was mainly from these planetesimals that the four outer planets eventually formed. The accumulation of ices accounts, in part, for the large sizes and low densities of the outer planets. The two most massive planets, Jupiter and Saturn, had surface gravities sufficient to attract and retain large quantities of hydrogen and helium, the lightest elements.

It took roughly 1 billion years after the protoplanets formed for the planets to gravitationally accumulate most of the interplanetary debris. This was a period of intense bombardment as the planets cleared their orbits by collecting much of the leftover material. The "scars" of this period are still evident on the Moon's surface. Because of the gravitational effect of the planets, particularly Jupiter, small bodies were flung into planet-crossing orbits or into interstellar space. The small fraction of interplanetary matter that escaped this violent period became either asteroids or comets. By comparison, the present-day solar system is a much quieter place, although many of these processes continue today at a reduced pace.

The Planets: Internal Structures and Atmospheres

The planets fall into two groups, based on location, size, and density: the **terrestrial (Earth-like) planets** (Mercury, Venus, Earth, and Mars) and the **Jovian (Jupiter-like) planets** (Jupiter, Saturn, Uranus, and Neptune). Because of their relative locations, the four terrestrial planets are also known as *inner planets*, and the four Jovian planets are known as *outer planets*. A correlation exists between planetary locations and sizes: The inner planets are substantially smaller than the outer planets, also known as *gas giants*. For example, the diameter of Neptune (the smallest Jovian planet) is nearly 4 times larger than the diameter of Earth. Furthermore, Neptune's mass is 17 times greater than that of Earth or Venus.

Other properties that differ among the planets include densities, chemical compositions, orbital periods, and numbers of satellites. Variations in the chemical composition of planets are largely responsible for their density differences. Specifically, the average density of the terrestrial planets is about 5 times the density of water, whereas the average density of the Jovian planets is only 1.5 times that of water. In fact, Saturn has a density only 0.7 times that of water, which means that it would float in a sufficiently large tank of water. The outer planets are also characterized by long orbital periods and numerous satellites.

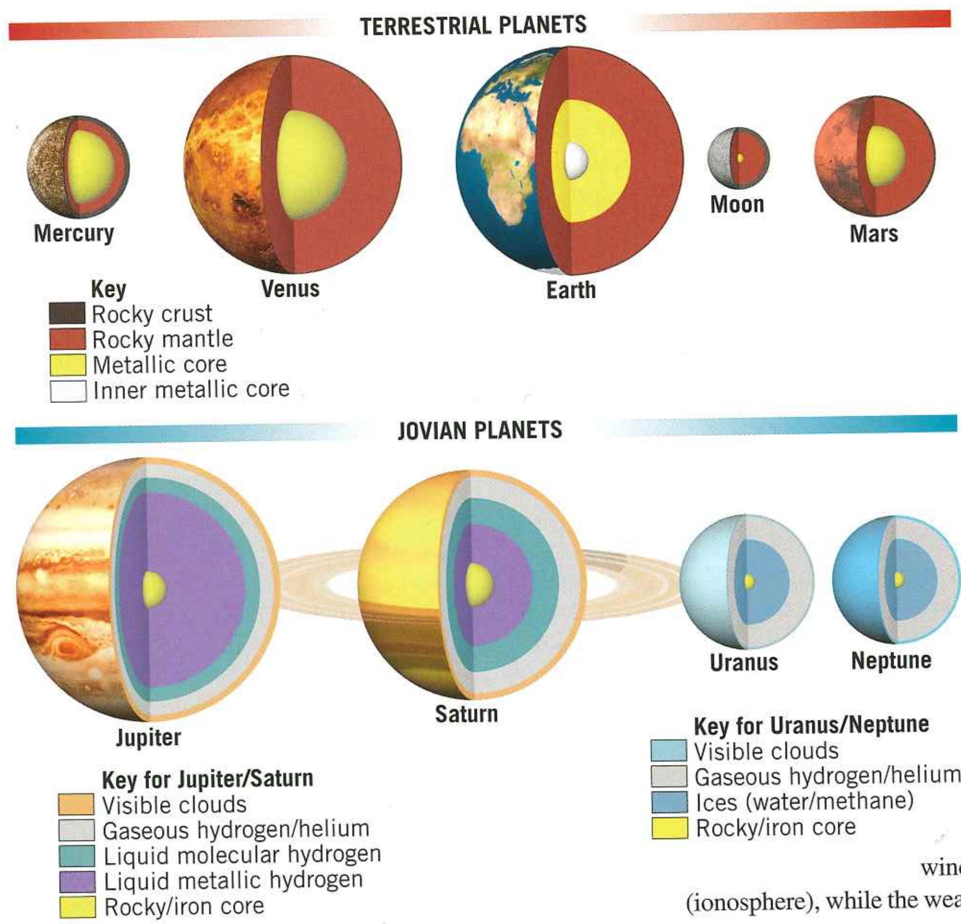


FIGURE 22.2 Comparing Internal Structures of the Planets

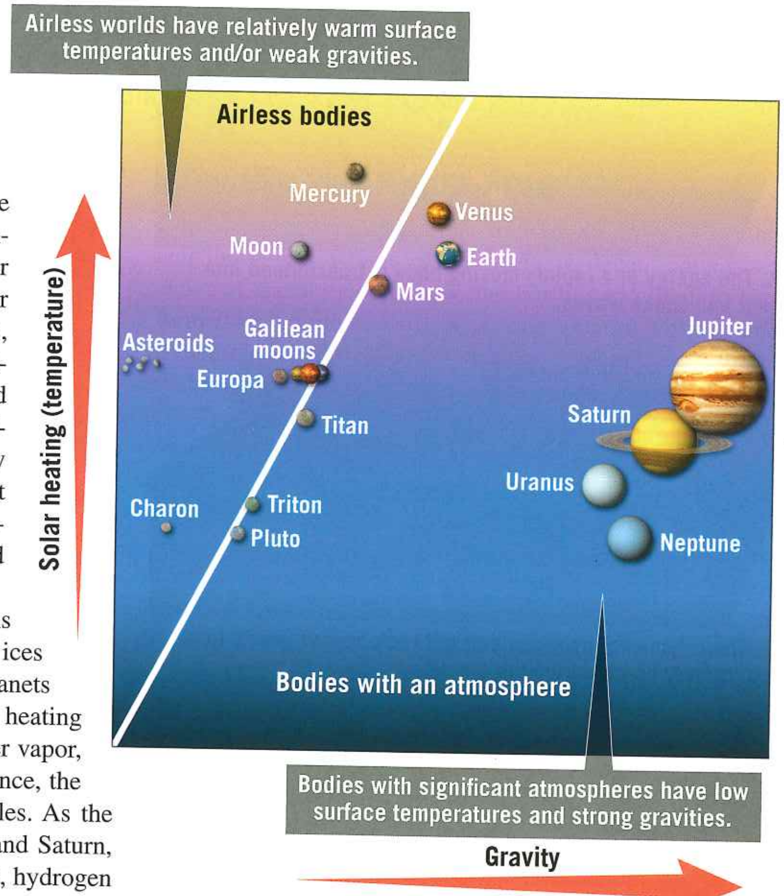
Internal Structures Shortly after Earth formed, segregation of material resulted in the formation of three major layers, defined by their chemical composition—the crust, mantle, and core. This type of chemical separation occurred in the other planets as well. However, because the terrestrial planets are compositionally different from the Jovian planets, the nature of these layers is different as well (**FIGURE 22.2**).

The terrestrial planets are dense, having relatively large cores of iron and nickel. The outer cores of Earth and Mercury are liquid, whereas the cores of Venus and Mars are thought to be only partially molten. This difference is attributable to Venus and Mars having lower internal temperatures than those of Earth and Mercury. Silicate minerals and other lighter compounds make up the mantles of the terrestrial planets. Finally, the silicate crusts of terrestrial planets are relatively thin compared to their mantles.

The two largest Jovian planets, Jupiter and Saturn, likely have small, solid cores consisting of iron compounds, like the cores of the terrestrial planets, and rocky material similar to Earth's mantle. Progressing outward, the layer above the core consists of liquid hydrogen that is under extremely high temperatures and pressures. There is substantial evidence that under these conditions, hydrogen behaves like a metal in that its electrons move freely about and are efficient conductors of both heat and electricity. Jupiter's intense magnetic field is thought to be the result of electric currents flowing within a spinning layer of liquid metallic hydrogen. Saturn's magnetic field is much weaker than Jupiter's, due to its smaller shell of liquid metallic hydrogen. Above this metallic layer, both Jupiter and Saturn are thought to be composed of molecular liquid hydrogen that is intermixed with helium. The outermost layers are gases of hydrogen and helium, as well as ices of water, ammonia, and methane—which mainly account for the low densities of these giants.

Uranus and Neptune also have small iron-rich, rocky cores, but their mantles are likely hot, dense water and ammonia. Above their mantles, the amount of hydrogen and helium increases, but these gases exist in much lower concentrations than in Jupiter and Saturn.

All planets, except Venus and Mars, have significant magnetic fields generated by flow of metallic materials in their liquid cores, or mantles. Venus has a weak field due to the interaction between the solar wind and its uppermost atmosphere (ionosphere), while the weak Martian magnetic field is thought to be a remnant from when its interior was hotter. Magnetic fields play an important role in protecting a planet's surface from bombardment by charged particles of the solar wind—a necessary condition for the survival of life-forms.



SmartFigure 22.3 Bodies with Atmospheres Versus Airless Bodies Two factors largely explain why some solar system bodies have thick atmospheres, whereas others are airless. Airless worlds have relatively warm surface temperatures and/or weak gravities. Bodies with significant atmospheres have low surface temperatures and strong gravities.

The Atmospheres of the Planets

The Jovian planets have very thick atmospheres composed mainly of hydrogen and helium, with lesser amounts of water, methane, ammonia, and other hydrocarbons. By contrast, the terrestrial planets, including Earth, have relatively meager atmospheres composed of carbon dioxide, nitrogen, and oxygen. Two factors explain these significant differences—solar heating (temperature) and gravity (**FIGURE 22.3**). These variables determine what planetary gases, if any, were captured by planets during the formation of the solar system and which were ultimately retained.

During planetary formation, the inner regions of the developing solar system were too hot for ices and gases to condense. By contrast, the Jovian planets formed where temperatures were low and solar heating of planetesimals was minimal. This allowed water vapor, ammonia, and methane to condense into ices. Hence, the gas giants contain large amounts of these volatiles. As the planets grew, the largest Jovian planets, Jupiter and Saturn, also attracted large quantities of the lightest gases, hydrogen and helium.

How did Earth acquire water and other volatile gases? It seems that early in the history of the solar system, gravitational tugs by the developing protoplanets sent planetesimals into very eccentric orbits. As a result, Earth was bombarded with icy objects that originated beyond the orbit of Mars. This was a fortuitous event for organisms that currently inhabit our planet. Mercury, our Moon, and numerous other small bodies lack significant atmospheres, even though they certainly would have been bombarded by icy bodies early in their development.

Airless bodies develop where solar heating is strong and/or gravities are weak. Simply stated, *small warm bodies* have a better chance of losing their atmospheres because gas molecules are more energetic and need less speed to escape their weak gravities. For example, warm bodies with small surface gravity, such as our Moon, are unable to hold even heavy gases such as carbon dioxide and nitrogen. Mercury is massive enough to hold trace amounts of hydrogen, helium, and oxygen gas.

The slightly larger terrestrial planets, Earth, Venus, and Mars, retain some heavy gases, including water vapor, nitrogen, and carbon dioxide. However, their atmospheres are miniscule compared to their total mass. Early in their development, the terrestrial planets probably had much thicker atmospheres. Over time, however, these primitive atmospheres gradually changed as light gases trickled away into space. For example, Earth's atmosphere continues to leak hydrogen and helium (the two lightest gases) into space. This phenomenon occurs near the top of Earth's atmosphere, where air is so tenuous that nothing stops the fastest-moving particles from flying off into space. The speed required to escape a planet's gravity is called **escape velocity**. Because hydrogen is the lightest gas, it most easily reaches the speed needed to overcome Earth's gravity.

Billions of years in the future, the loss of hydrogen (one of the components of water) will eventually "dry out" Earth's oceans, ending its hydrologic cycle. Life, however, may remain sustainable in Earth's polar regions.

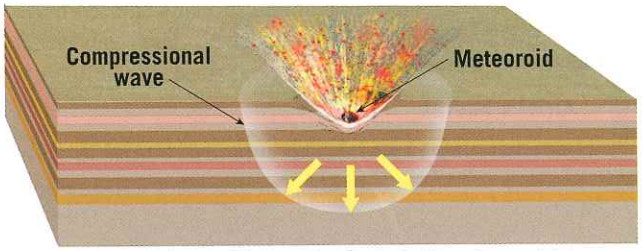
The massive Jovian planets have strong gravitational fields and thick atmospheres. Furthermore, because of their great distance from the Sun, solar heating is minimal. This explains why Saturn's moon Titan, which is small compared to Earth but much further from the Sun, retains an atmosphere. Because the molecular motion of a gas is temperature dependent, even hydrogen and helium move too slowly to escape the gravitational pull of the Jovian planets.

Planetary Impacts

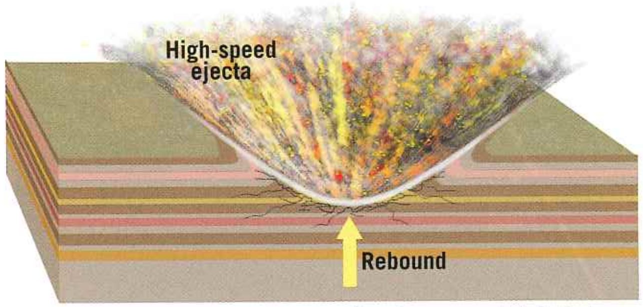
Planetary impacts between solar system bodies have occurred throughout the history of the solar system. On bodies that have little or no atmosphere (like the Moon) and, therefore, no air resistance, even the smallest pieces of interplanetary debris (meteorites) can reach the surface. At high enough velocities, this debris can produce microscopic cavities on individual mineral grains. By contrast, large **impact craters** result from collisions with massive bodies, such as asteroids and comets.

Planetary impacts were considerably more common in the early history of the solar system than they are today.

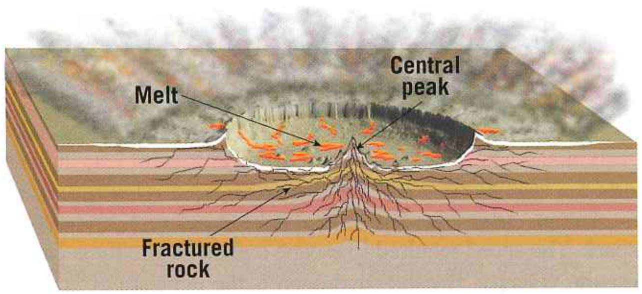
FIGURE 22.4 Formation of an Impact Crater



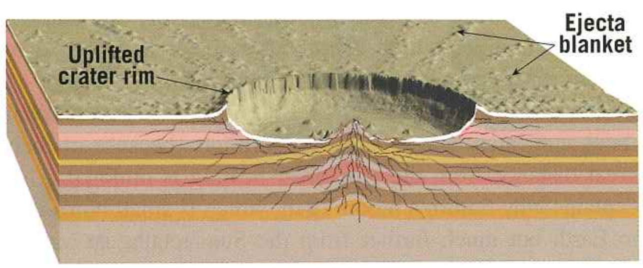
A. The energy of a rapidly moving body is transformed into heat and shock waves.



B. The rebound of over-compressed rock causes debris to be explosively ejected from the crater.



C. Heating melts some material that may be ejected from the crater as glass beads.



D. Small secondary craters often form when the material "splashed" from the impact crater strikes the surrounding landscape.

Following that early period of intense bombardment, the rate of cratering diminished dramatically and now remains essentially constant. Because weathering and erosion are almost nonexistent on the Moon and Mercury, evidence of their cratered past is clearly evident.

On larger bodies, thick atmospheres may cause the impacting objects to break up and/or decelerate. For example, Earth's atmosphere causes meteoroids with masses of less than 10 kilograms (22 pounds) to lose up to 90 percent of their speed as they penetrate the atmosphere. Therefore, impacts of low-mass bodies produce only small craters on Earth. Our atmosphere is much less effective in slowing large bodies; fortunately, they make very rare appearances.

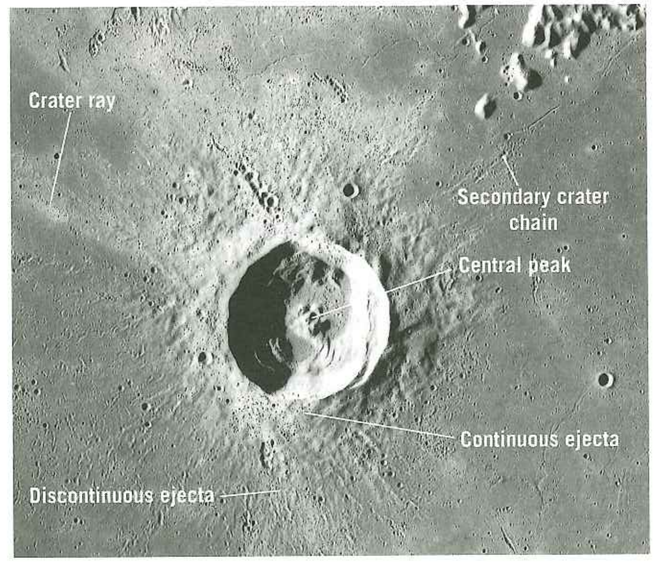


FIGURE 22.5 Lunar Crater Euler This 20-kilometer-wide (12-mile-wide) crater is located in the southwestern part of Mare Imbrium. Clearly visible are the bright rays, central peak, secondary craters, and large accumulation of ejecta near the crater rim. (Courtesy of NASA)

The formation of a large impact crater is illustrated in **FIGURE 22.4**. The meteoroid's high-speed impact compresses the material it strikes, causing an almost instantaneous rebound, which ejects material from the surface. On Earth, impacts can occur at speeds that exceed 50 kilometers (30 miles) per second. Impacts at such high speeds produce shock waves that compress both the impactor and the material being impacted. Almost instantaneously, the over-compressed material rebounds and explosively ejects material out of the newly formed crater. This process is analogous to the detonation of an explosive device that has been buried underground.

Craters excavated by objects that are several kilometers across often exhibit a central peak, such as the one in the large crater in **FIGURE 22.5**. Much of the material expelled, called *ejecta*, lands in or near the crater, where it accumulates to form a rim. Large meteoroids may generate sufficient heat to melt and eject some of the impacted rock as glass beads. Specimens of glass beads produced in this manner, as well as melt breccia consisting of broken fragments welded by the heat of impact, have been collected on Earth, as well as the Moon, allowing planetary geologists to more fully understand such events.

22.1 CONCEPT CHECKS

1. Briefly outline the steps in the formation of our solar system, according to the nebular theory.
2. By what criteria are planets considered either terrestrial or Jovian?
3. What accounts for the large density differences between the terrestrial and Jovian planets?
4. Explain why the terrestrial planets have meager atmospheres, as compared to the Jovian planets.
5. Why are impact craters more common on the Moon than on Earth, even though the Moon is a much smaller target and has a weaker gravitational field?
6. When did the solar system experience the period of heaviest planetary impacts?

22.2 EARTH'S MOON: A CHIP OFF THE OLD BLOCK

List and describe the major features of Earth's Moon and explain how maria basins were formed.

The Earth–Moon system is unique because the Moon is the largest satellite relative to its planet. Mars is the only other terrestrial planet that has moons, but its tiny satellites are likely captured asteroids. Most of the 150 or so satellites of the Jovian planets are composed of low-density rock–ice mixtures, none of which resemble the Moon. As we will see later, our unique planet–satellite system is closely related to the mechanism that created it.

The diameter of the Moon is 3475 kilometers (2160 miles), about one-fourth of Earth's 12,756 kilometers (7926 miles). The Moon's surface temperature averages about 107°C (225°F) during daylight hours and −153°C (−243°F) at night. Because its period of rotation on its axis equals its period of revolution around Earth, the same lunar hemisphere always faces Earth. All of the landings of staffed *Apollo* missions were confined to the side of the Moon that faces Earth.

The Moon's density is 3.3 times that of water, comparable to that of *mantle* rocks on Earth but considerably less than Earth's average density (5.5 times that of water). The Moon's relatively small iron core is thought to account for much of this difference.

The Moon's low mass relative to Earth results in a lunar gravitational attraction that is one-sixth that of Earth. A person who weighs 150 pounds on Earth weighs only 25 pounds on the Moon, although the person's mass remains the same. This difference allows an astronaut to carry a heavy life-support system with relative ease. If not burdened with such a load, an astronaut could jump six times higher on the Moon than on Earth. The Moon's small mass (and low gravity) is the primary reason it was not able to retain an atmosphere.

How Did the Moon Form?

Until recently, the origin of the Moon—our nearest planetary neighbor—was a topic of considerable debate among scientists. Current models show that Earth is too small to have formed with a moon, particularly one so large. Furthermore, a captured moon would likely have an eccentric orbit similar to the captured moons that orbit the Jovian planets.

The current consensus is that the Moon formed as a result of a collision between a Mars-sized body and a youthful, semimolten Earth about 4.5 billion years ago. During this collision, some of the ejected debris was thrown into orbit around Earth and gradually coalesced to form the Moon. Computer simulations show that most of the ejected material would have come from the rocky mantle of the impactor, while its core was assimilated into the growing Earth. This *impact model* is consistent with the Moon having a proportionately smaller core than Earth's and, hence, a lower density.

The Lunar Surface When Galileo first pointed his telescope toward the Moon, he observed two different types of terrain: dark lowlands and brighter, highly cratered highlands (**FIGURE 22.6**). Because the dark regions appeared to be smooth, resembling seas on Earth, they were called **maria** (*mar* = sea, singular *mare*). The *Apollo 11* mission showed conclusively that the maria are exceedingly smooth plains composed of basaltic lavas. These vast plains are strongly concentrated on the side of the Moon facing Earth and cover about 16 percent of the lunar surface. The lack of large volcanic cones on these surfaces is

EYE ON THE UNIVERSE

Mariner 9 obtained this image of Phobos, one of two tiny satellites of Mars. Phobos has a diameter of only 24 kilometers (15 miles). The two moons of Mars were not discovered until the late 1800s because their size made them nearly impossible to view telescopically. (Photo by NASA)

QUESTION 1 *In what way is Phobos similar to Earth's Moon?*

QUESTION 2 *List characteristics of Phobos that make it different from Earth's Moon.*

QUESTION 3 *Do an Internet search to learn how Phobos and its companion moon, Deimos, got their names.*

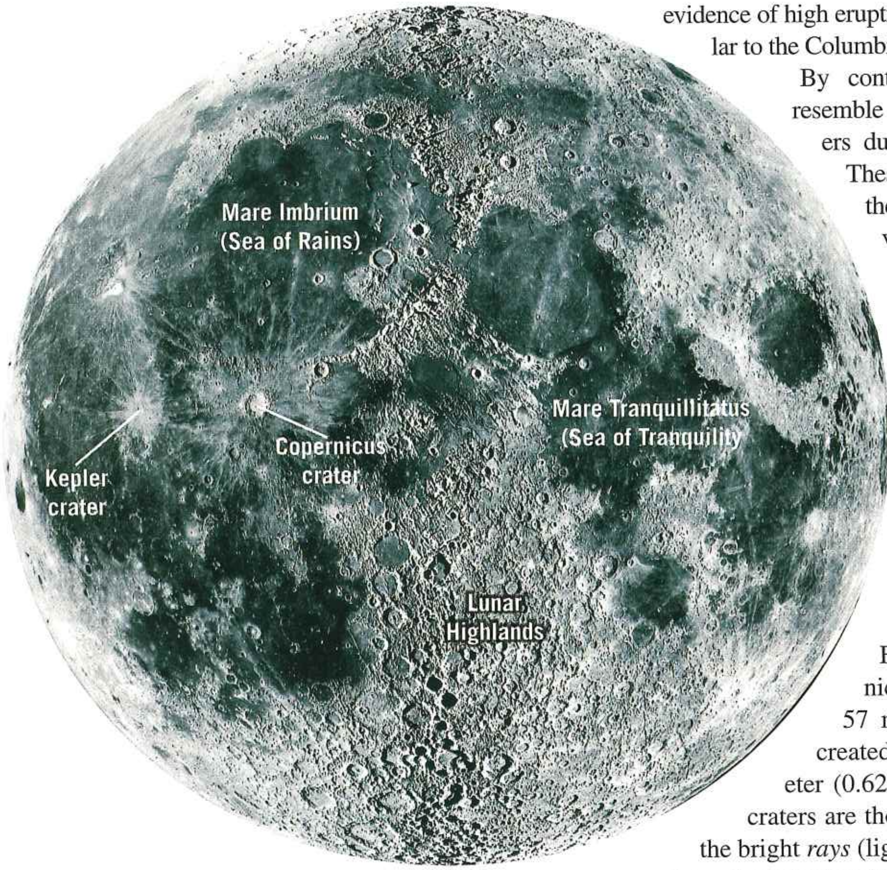


FIGURE 22.6 Telescopic View of the Lunar Surface The major features are the dark maria and the light, highly cratered highlands. (NASA)

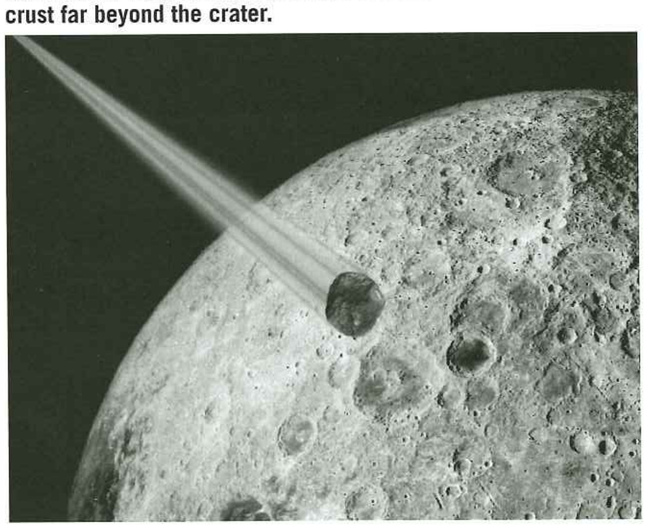
evidence of high eruption rates of very fluid basaltic lavas similar to the Columbia Plateau flood basalts on Earth.

By contrast, the Moon's light-colored areas resemble Earth's continents, so the first observers dubbed them **terrae** (Latin for "lands"). These areas are now generally referred to as the **lunar highlands** because they are elevated several kilometers above the maria. Rocks retrieved from the highlands are mainly breccias, pulverized by massive bombardment early in the Moon's history. The arrangement of terrae and maria has resulted in the legendary "face" of the "man in the Moon."

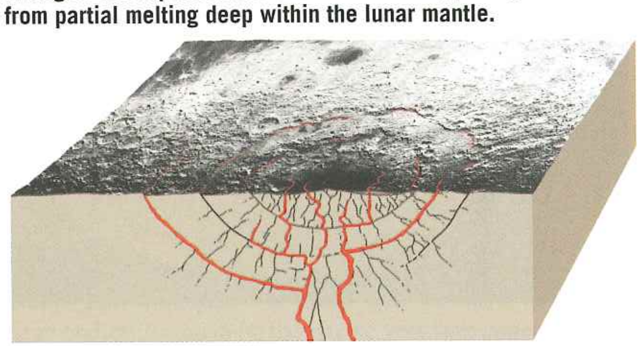
Some of the most obvious lunar features are impact craters. A meteoroid 3 meters (10 feet) in diameter can blast out a crater 50 times larger, or about 150 meters (500 feet) in diameter. The larger craters shown in Figure 22.6, such as Kepler and Copernicus (32 and 93 kilometers [20 and 57 miles] in diameter, respectively), were created from bombardment by bodies 1 kilometer (0.62 mile) or more in diameter. These two craters are thought to be relatively young because of the bright *rays* (light-colored ejected material) that radiate from them for hundreds of kilometers.

SmartFigure 22.7 Formation and Filling of Large Impact Basins
(Photo © UC Regents/Lick Observatory)

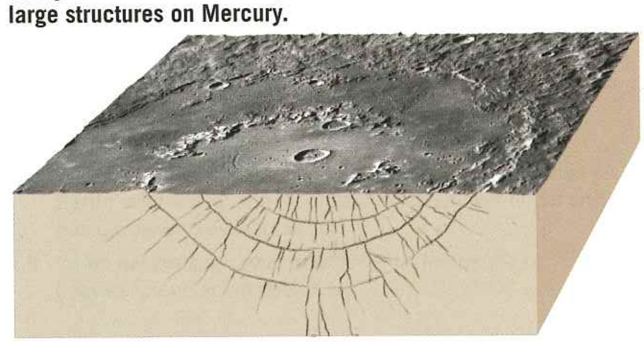
Impact of an asteroid-size body produced a huge crater hundreds of kilometers in diameter and disturbed the lunar crust far beyond the crater.



Filling of the impact crater with fluid basalts, perhaps derived from partial melting deep within the lunar mantle.



Today these basins make up the lunar maria and a few similar large structures on Mercury.



History of the Lunar Surface

The evidence used to unravel the history of the lunar surface comes primarily from radiometric dating of rocks returned from *Apollo* missions and studies of crater densities—counting the number of craters per unit area. The greater the crater density, the older the feature is inferred to be. Such evidence suggests that, after the Moon coalesced, it passed through the following four phases: (1) formation of the original crust, (2) excavation of the large impact basins, (3) filling of maria basins, and (4) formation of rayed craters.

During the late stages of its accretion, the Moon's outer shell was most likely completely melted—literally a magma ocean. Then, about 4.4 billion years ago, the magma ocean began to cool and underwent magmatic differentiation (see Chapter 4). Most of the dense minerals, olivine and pyroxene, sank, while less-dense silicate minerals floated to form the Moon's crust. The highlands are made of these igneous

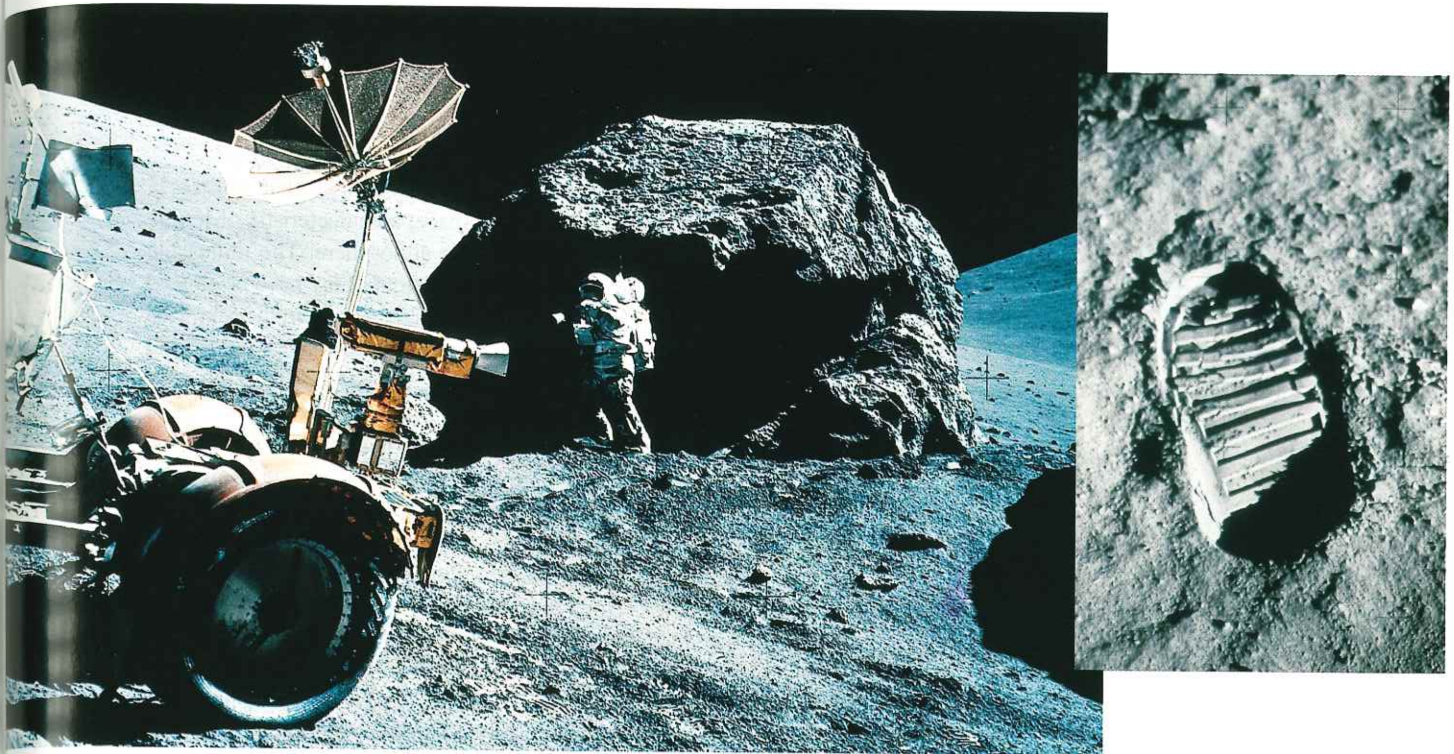


FIGURE 22.8 Astronaut Harrison Schmitt, Sampling the Lunar Surface Notice the footprint (inset) in the lunar "soil," called regolith, which lacks organic material and is therefore not a true soil. (Courtesy of NASA)

rocks, which rose buoyantly like "scum" from the crystallizing magma. The most common highland rock type is *anorthosite*, which is composed mainly of calcium-rich plagioclase feldspar.

Once formed, the lunar crust was continually impacted as the Moon swept up debris from the solar nebula. During this time, several large impact basins were created. Then, about 3.8 billion years ago, the Moon, as well as the rest of the solar system, experienced a sudden drop in the rate of meteoritic bombardment.

The Moon's next major event was the filling of the large impact basins, which were created at least 300 million years earlier (**FIGURE 22.7**). Radiometric dating of the maria basalts puts their age between 3.0 billion and 3.5 billion years, considerably younger than the initial lunar crust.

The maria basalts are thought to have originated at depths between 200 and 400 kilometers (125 and 250 miles). They were likely generated by a slow rise in temperature attributed to the decay of radioactive elements. Partial melting probably occurred in several isolated pockets, as indicated by the diverse chemical makeup of the rocks retrieved during the *Apollo* missions. Recent evidence suggests that some mare-forming eruptions may have occurred as recently as 1 billion years ago.

Other lunar surface features related to this period of volcanism include small shield volcanoes (8–12 kilometers [5–7.5 miles] in diameter), evidence of pyroclastic eruptions, rilles (narrow winding valleys thought to be lava channels), and grabens (down-faulted valleys).

The last prominent features to form were rayed craters, as exemplified by the 90-kilometer-wide (56-mile-wide) Copernicus crater shown in Figure 22.7. Material ejected from these craters blankets the maria surfaces and many older, rayless craters. The relatively young Copernicus crater is thought to be about 1 billion years old. Had it formed on Earth, weathering and erosion would have long since obliterated it.

Today's Lunar Surface The Moon's small mass and low gravity account for its lack of atmosphere and flowing water. The processes of weathering and erosion that continually modify Earth's surface are absent on the Moon. In addition, tectonic forces are no longer active on the Moon, so quakes and volcanic eruptions have ceased. Because the Moon is unprotected by an atmosphere, erosion is dominated by the impact of tiny particles from space (*micrometeorites*) that continually bombard its surface and gradually smooth the landscape. This activity has crushed and repeatedly mixed the upper portions of the lunar crust.

Both the maria and terrae are mantled with a layer of gray, unconsolidated debris derived from a few billion years of meteoric bombardment (**FIGURE 22.8**). This soil-like layer, properly called **lunar regolith** (*rhegos* = blanket, *lithos* = stone), is composed of igneous rocks, breccia, glass beads, and fine *lunar dust*. The lunar regolith is anywhere from 2 to 20 meters (6.5 to 65 feet) thick, depending on the age of the surface.

22.2 CONCEPT CHECKS

1. Briefly describe the origin of the Moon.
2. Compare and contrast the Moon's maria and highlands.
3. How are maria on the Moon similar to the Columbia Plateau in the Pacific Northwest?
4. How is crater density used in the relative dating of surface features on the Moon?
5. List the major stages in the development of the modern lunar surface.
6. Compare and contrast the processes of weathering and erosion on Earth with the same processes on the Moon.

22.3 TERRESTRIAL PLANETS

Outline the principal characteristics of Mercury, Venus, and Mars. Describe their similarities to and differences from Earth.

The terrestrial planets, in order from the Sun, are Mercury, Venus, Earth, and Mars. Because most of the book focuses on Earth, we consider the three other Earth-like planets next.

Mercury: The Innermost Planet

Mercury, the innermost and smallest planet, revolves around the Sun quickly (88 days) but rotates slowly on its axis. Mercury's day–night cycle, which lasts 176 Earth-days, is very long compared to Earth's 24-hour cycle. One "night" on Mercury is roughly equivalent to 3 months on Earth and is followed by the same duration of daylight. Mercury has the greatest temperature extremes, from as low as −173°C (−280°F) at night to noontime temperatures exceeding 427°C (800°F), hot enough to melt tin and lead. These extreme temperatures make life as we know it impossible on Mercury.

Mercury absorbs most of the sunlight that strikes it, reflecting only 6 percent into space, a characteristic of terrestrial bodies that have little or no atmosphere. The minuscule amount of gas that is present on Mercury may have originated from several sources, including ionized gas from the Sun, ices that vaporized during a recent comet impact, and/or outgassing of the planet's interior.

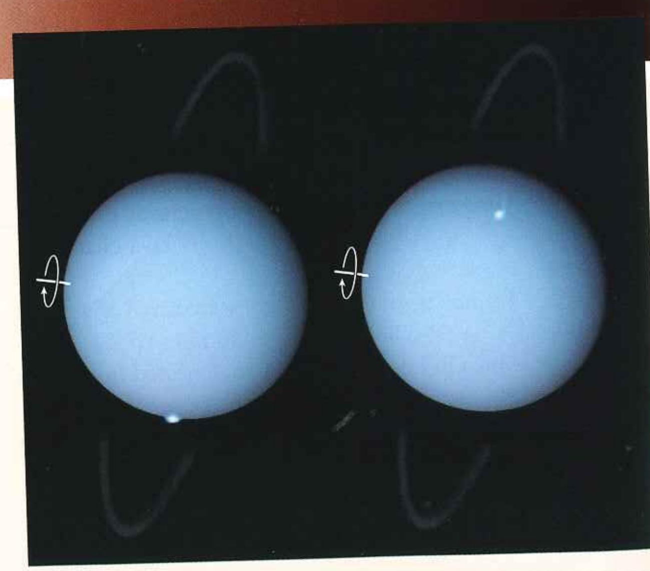
Although Mercury is small and scientists expected the planet's interior to have already cooled, *Mariner 10* measured Mercury's magnetic field in 2012. It found Mercury's magnetic field to be about 100 times less than Earth's, which suggests that Mercury has a large core that remains hot and fluid—a requirement for generating a magnetic field.

Mercury resembles Earth's Moon in that it has very low reflectivity, no sustained atmosphere, numerous volcanic features, and a heavily cratered terrain (**FIGURE 22.9**). The largest-known impact crater (1300 kilometers [800 miles] in diameter) on Mercury is Caloris Basin. Images and other data gathered by *Mariner 10* show evidence of volcanism in and around Caloris Basin and a few other smaller basins. Also like our Moon, Mercury has smooth plains that cover nearly 40 percent of the area imaged by *Mariner 10*. Most of these smooth areas are associated with large impact basins, including Caloris Basin, where lava partially filled the basins and the surrounding lowlands. Consequently, these smooth plains appear to be similar in origin to lunar maria. Recently, *Messenger* found evidence

FIGURE 22.9 Two Views of Mercury On the left is a monochromatic image, while the image on the right is color enhanced. These are high-resolution mosaics constructed from thousands of images obtained by the *Messenger* orbiter. (Courtesy of NASA)

EYE ON THE UNIVERSE

In 2012, the Hubble Space Telescope captured these images of auroras above the giant planet Uranus. These light shows on Uranus appear to last for only a few minutes and consist of faint glowing dots. These are unlike auroras on Earth, which can color the sky shades of green, red, or purple for hours. (Photo by NASA)



QUESTION 1 *What is unusual about the location of the auroras on Uranus?*

QUESTION 2 *What does this indicate about the locations of Uranus's "north" and "south" magnetic poles?*

of volcanism by revealing thick volcanic deposits similar to those on Earth in the Columbia Basin. In addition, researchers were surprised by the recent detection of probable ice caps on Mercury.

Venus: The Veiled Planet

Venus, second only to the Moon in brilliance in the night sky, is named for the Roman goddess of love and beauty. It orbits the Sun in a nearly perfect circle once every 225 Earth-days. However, Venus rotates in the opposite direction of the other planets (*retrograde motion*) at an agonizingly slow pace: 1 Venus day is equivalent to about 244 Earth days. Venus has the densest atmosphere of the terrestrial planets, consisting mostly of carbon dioxide (97 percent)—the prototype for an extreme *greenhouse effect*. As a consequence, the surface temperature of Venus averages about 450°C (900°F) day and night. Temperature variations at the surface are generally minimal because of the intense mixing within the planet's dense atmosphere. Investigations of the extreme and uniform surface temperature led scientists to more fully understand how the greenhouse effect operates on Earth.

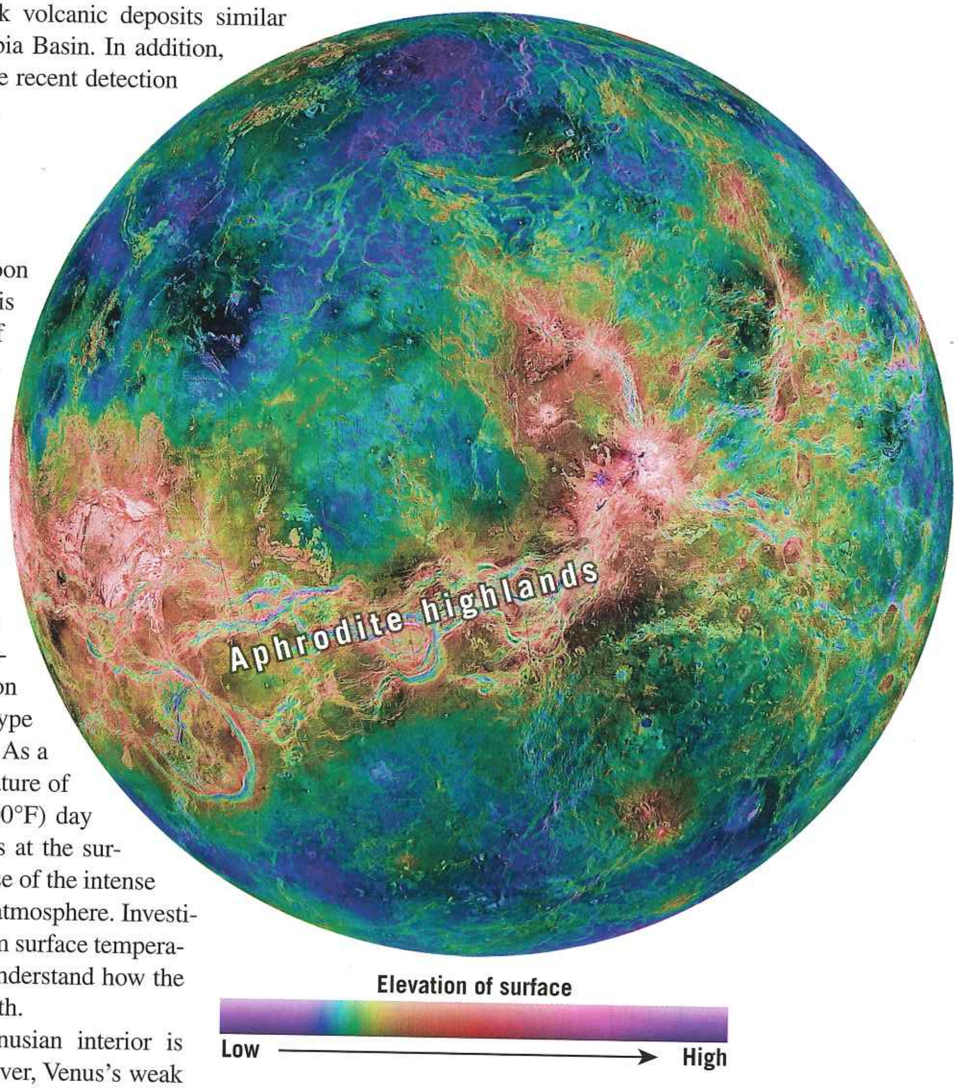


FIGURE 22.10 Global View of the Surface of Venus This computer-generated image of Venus was constructed from years of investigations, culminating with the *Magellan* mission. The twisting bright features that cross the globe are highly fractured ridges and canyons of the eastern Aphrodite highland. (Courtesy of NASA)

The composition of the Venusian interior is probably similar to Earth's. However, Venus's weak magnetic field means its internal dynamics must be very different from Earth's. Mantle convection is thought to operate on Venus, but the processes of plate tectonics, which recycle rigid lithosphere, do not appear to have contributed to the present Venusian topography.

The surface of Venus is completely hidden from view by a thick cloud layer composed mainly of tiny sulfuric acid droplets. In the 1970s, despite extreme temperatures and pressures, four Russian spacecraft landed successfully and obtained surface images. As expected, however, all the probes were crushed by the planet's immense atmospheric pressure, approximately 90 times that on Earth, within an hour of landing. Using radar imaging, the unstaffed spacecraft *Magellan* mapped Venus's surface in stunning detail (**FIGURE 22.10**).

A few thousand impact craters have been identified on Venus—far fewer than on Mercury and Mars but more than on Earth. Researchers expected that Venus would show evidence of extensive cratering from the heavy bombardment period but found instead that a period of extensive volcanism was responsible for resurfacing Venus. The planet's thick atmosphere also limits the number of impacts by breaking up large incoming meteoroids and incinerating most of the small debris.

About 80 percent of the Venusian surface consists of low-lying plains covered by lava flows, some of which traveled along lava channels that extend hundreds of kilometers (**FIGURE 22.11**). Venus's Baltis Vallis, the longest-known lava channel in the solar system, meanders 6800 kilometers (4255 miles) across the planet. More than 1000 volcanoes with diameters greater than 20 kilometers (12 miles) have been identified on Venus. However, high surface pressures keep the gaseous components in lava from escaping. This retards the production of pyroclastic material and lava fountaining, phenomena that tend to steepen volcanic cones. In addition, because of Venus's high temperature, lava remains mobile longer and thus flows far from the vent. Both of these factors result in volcanoes that tend to be shorter and wider than those on Earth or Mars (**FIGURE 22.12**). Maat Mons, the largest volcano on Venus, is about 8.5 kilometers high (5 miles) and 400 kilometers (250 miles) wide. By comparison, Mauna Loa, the largest volcano on Earth, is about 9 kilometers high (5.5 miles) and only 120 kilometers (75 miles) wide.

Venus also has major highlands that consist of plateaus, ridges, and topographic rises that stand above the plains. The rises are thought to have formed where hot mantle plumes encountered the base of the planet's crust, causing uplift. Much as with mantle plumes on Earth, abundant volcanism is associated with mantle upwelling on Venus. Recent data

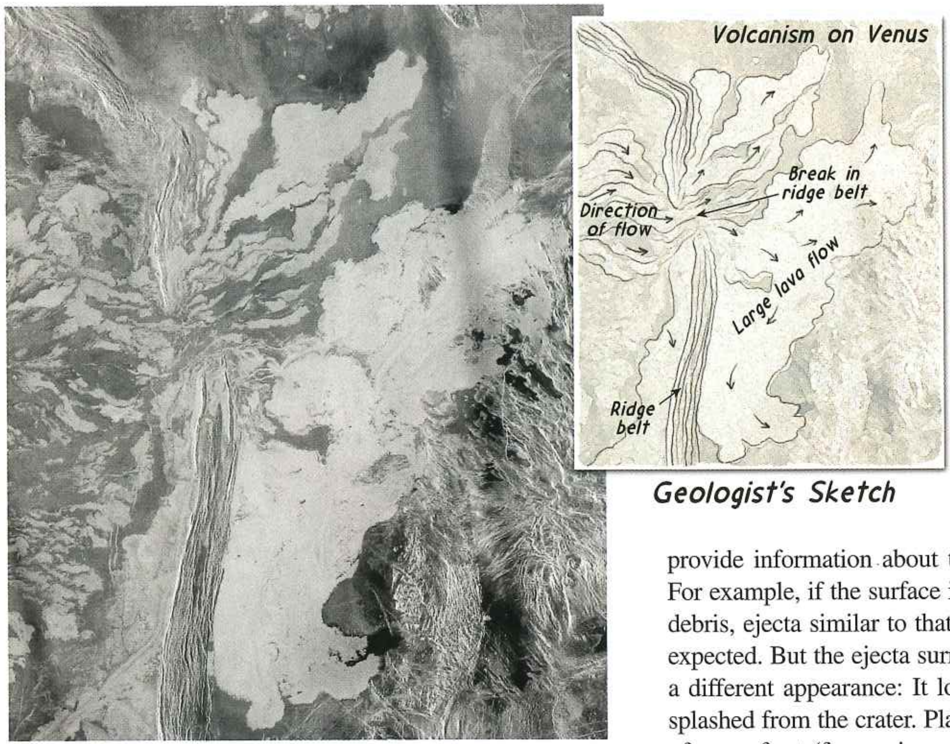


FIGURE 22.11 Extensive Lava Flows on Venus This *Magellan* radar image shows a system of lava flows that originated from a volcano named Ammavaru, which lies approximately 300 kilometers (186 miles) west of the scene. The lava, which appears bright in this radar image, has rough surfaces, whereas the darker flows are smooth. Upon breaking through the ridge belt (left of center), the lava collected in a 100,000-square-kilometer pool. (Courtesy of NASA)

collected by the European Space Agency's *Venus Express* suggest that Venus's highlands contain silica-rich granitic rock. As such, these elevated landmasses resemble Earth's continents, albeit on a much smaller scale.

Mars: The Red Planet

Mars, approximately one-half the diameter of Earth, revolves around the Sun in 687 Earth-days. Mean surface temperatures range from lows of −140°C (−220°F) at the poles in the winter to highs of 20°C (68°F) at the equator in the summer. Although seasonal temperature variations are similar to Earth's, daily temperature variations are greater due to the very thin atmosphere of Mars (only 1 percent as dense as Earth's). The tenuous Martian atmosphere consists primarily of carbon dioxide (95 percent), with small amounts of nitrogen, oxygen, and water vapor.

Topography Mars, like the Moon, is pitted with impact craters. The smaller craters are usually filled with wind-blown dust—confirming that Mars is a dry, desert world. The reddish color of the Martian landscape is due to iron oxide (rust). Large impact craters provide information about the nature of the Martian surface. For example, if the surface is composed of dry dust and rocky debris, ejecta similar to that surrounding lunar craters is to be expected. But the ejecta surrounding some Martian craters has a different appearance: It looks like a muddy slurry that was splashed from the crater. Planetary geologists infer that a layer of permafrost (frozen, icy soil) lies below portions of the Martian surface and that impacts heated and melted the ice to produce the fluid-like appearance of these ejecta.

About two-thirds of the surface of Mars consists of heavily cratered highlands, concentrated mostly in its southern hemisphere (**FIGURE 22.13**). The period of extreme cratering occurred early in the planet's history and ended about 3.8 billion years ago, as it did in the rest of the solar system. Thus, Martian highlands are similar in age to the lunar highlands.

Based on relatively low crater counts, the northern plains, which account for the remaining one-third of the planet, are younger than the highlands. If Mars once had abundant water, it would have flowed to the north, which is lower in elevation, forming an expansive ocean (shown in blue in Figure 22.13, indicating lower elevation). The relatively flat topography of the northern plains, possibly the smoothest surface in the solar system, is consistent with vast outpourings of fluid basaltic lavas. Visible on these plains are volcanic cones, some with summit pits (craters) and lava flows with wrinkled edges.

Located along the Martian equator is an enormous elevated region, about the size of North America, called the *Tharsis bulge*. This feature, about 10 kilometers (6 miles) high, appears to have been uplifted and capped with a massive accumulation of volcanic rock that includes the solar system's largest volcanoes.

The tectonic forces that created the Tharsis region also produced fractures that radiate from its center, like spokes on a bicycle wheel. Along the

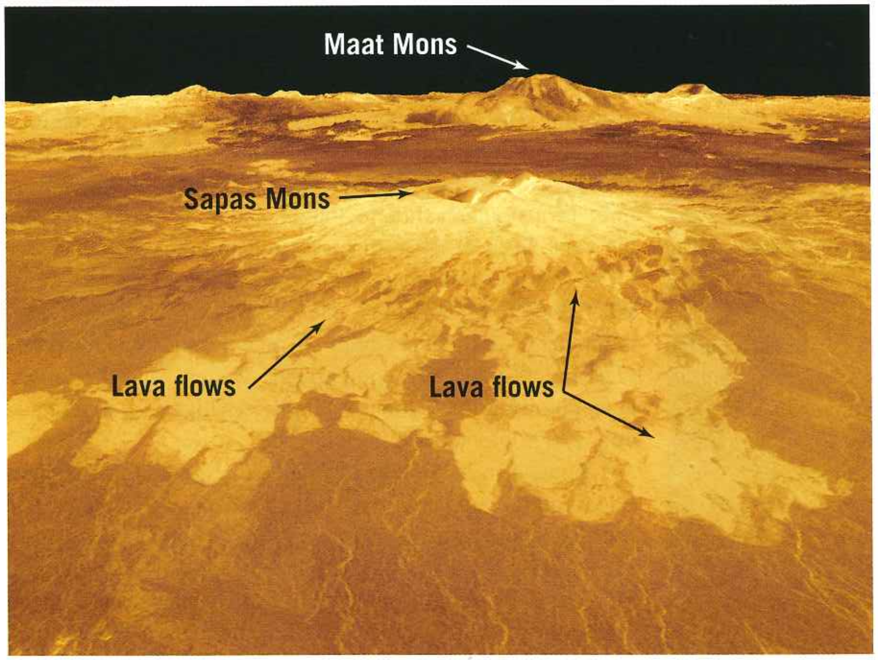


FIGURE 22.12 Volcanoes on Venus Sapas Mons is a broad volcano, 400 kilometers (250 miles) wide. The bright areas in the foreground are lava flows. Another large volcano, Maat Mons, is in the background. (Courtesy of NASA)

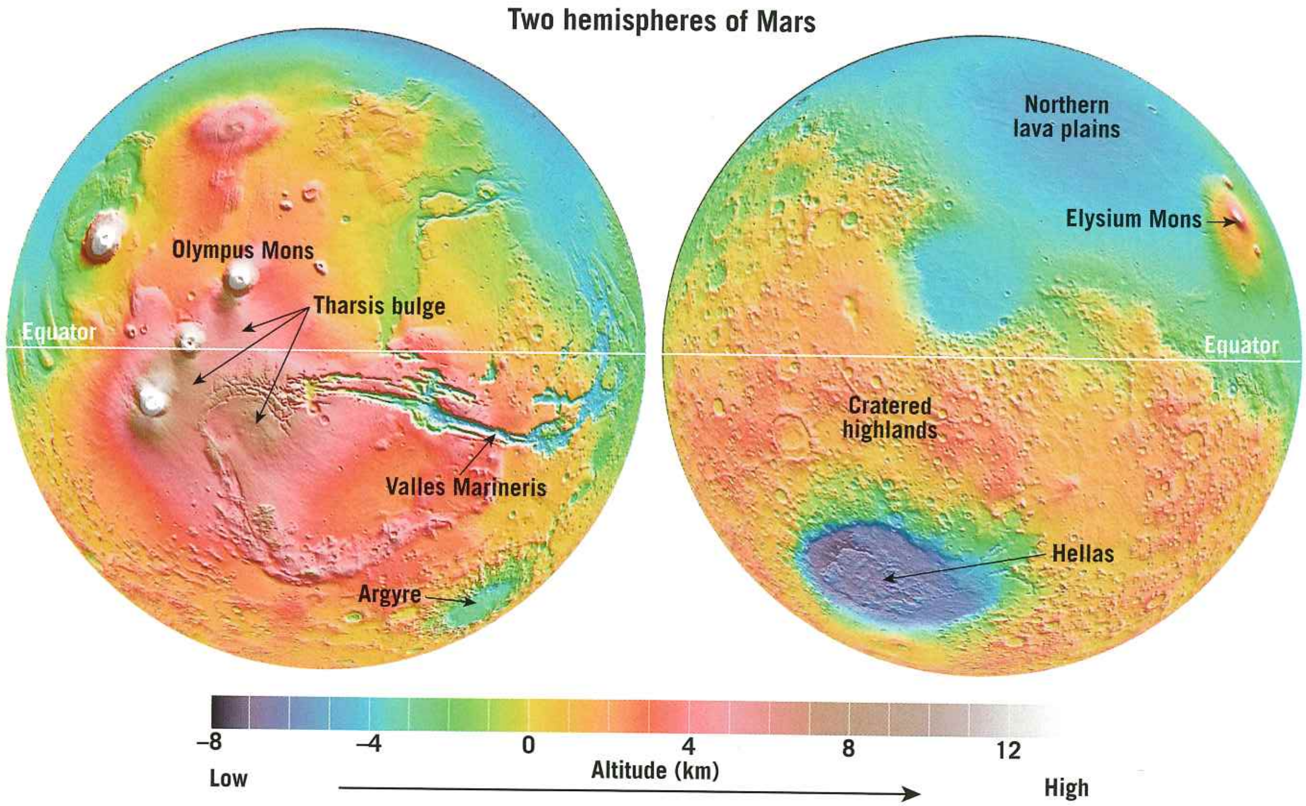


FIGURE 22.13 Two Hemispheres of Mars Color represents height above (or below) the mean planetary radius: White is about 12 kilometers above average, and dark blue is 8 kilometers below average. (Courtesy of NASA)

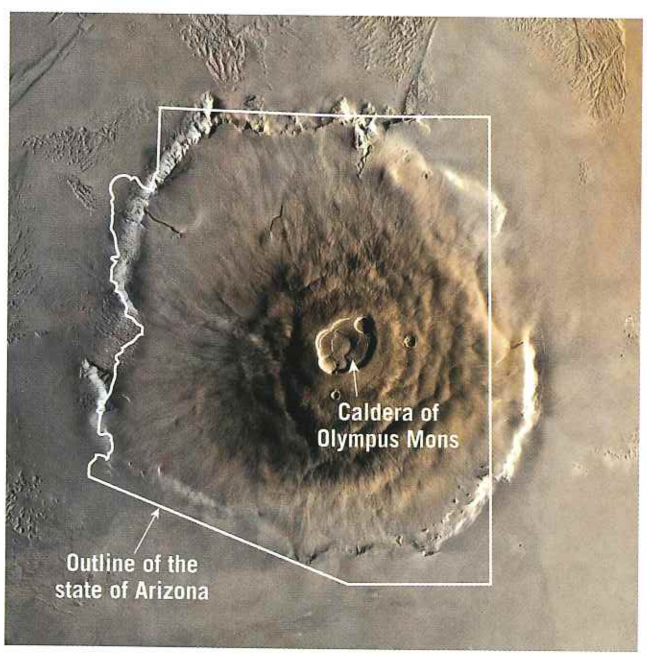
eastern flanks of the bulge, a series of vast canyons called *Valles Marineris* (Mariner Valleys) developed. Valles Marineris is so vast that it can be seen in the image of Mars in Figure 22.13. This canyon network was largely created by down-faulting, not by stream erosion, as is the case for Arizona's Grand Canyon. Thus, it consists of grabenlike valleys similar to the East African Rift valleys. Once formed, Valles Marineris grew by water erosion and collapse of the rift walls. The main canyon is more than 5000 kilometers (3000 miles) long, 7 kilometers (4 miles) deep, and 100 kilometers (60 miles) wide.

Other prominent features on the Martian landscape are large impact basins. Hellas, the largest identifiable impact structure on the planet, is about 2300 kilometers (1400 miles) in diameter and has the planet's lowest elevation. Debris ejected from this basin contributed to the elevation of the adjacent highlands. Other buried crater basins that are even larger than Hellas probably exist.

Volcanoes on Mars Volcanism has been prevalent on Mars during most of its history. The scarcity of impact craters on some volcanic surfaces suggests that the planet is still active. Mars has several of the largest-known volcanoes in the solar system, including the largest, Olympus Mons, which is about the size of Arizona and stands nearly three times higher than Mount Everest. This gigantic volcano was last active about 100 million years ago and resembles Earth's Hawaiian shield volcanoes (**FIGURE 22.14**).

How did the volcanoes on Mars grow so much larger than similar structures on Earth? The largest volcanoes on the terrestrial planets tend to form where plumes of hot rock rise from deep within their interiors. On Earth, moving plates keep the crust in constant motion. Consequently, mantle plumes tend to produce a chain of volcanic structures, like the Hawaiian islands. By contrast, plate tectonics on Mars is absent, so successive eruptions accumulate in the same location. As a result, enormous volcanoes such as Olympus Mons form rather than a string of smaller ones.

Wind Erosion on Mars Currently, the dominant force shaping the Martian surface is wind erosion. Extensive dust storms, with winds up to 270 kilometers (170 miles) per hour, can persist for weeks. Dust devils have also been photographed.



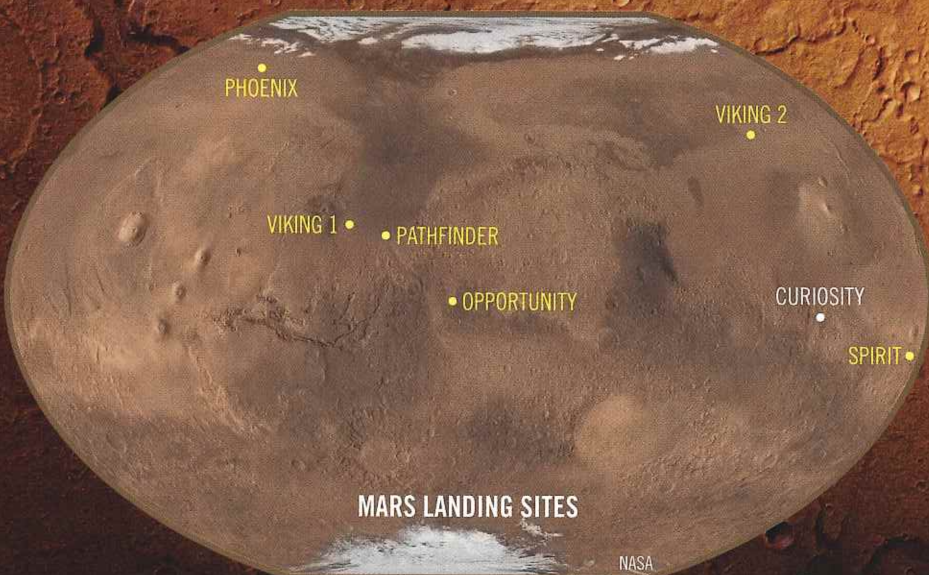
SmartFigure 22.14 Olympus Mons This massive inactive shield volcano on Mars covers an area about the size of the state of Arizona. (Courtesy of NASA)

Mars Exploration

Since the first close-up picture of Mars was obtained in 1965, spacecraft voyages to the fourth planet from the Sun have revealed a world that is strangely familiar. Mars has a thin atmosphere, polar ice caps, volcanoes, lava plains, sand dunes, and seasons. Unlike Earth, Mars appears to lack liquid water on its surface; however, many Martian landscapes suggest that, in the past, running water was an effective erosion agent. The defining question for Mars exploration is "has Mars ever harbored life?"

NASA's Phoenix lander dug into the Martian surface to uncover water ice in a northern region of the planet. Whether ice becomes available as liquid water to support microbial life remains unanswered.

NASA



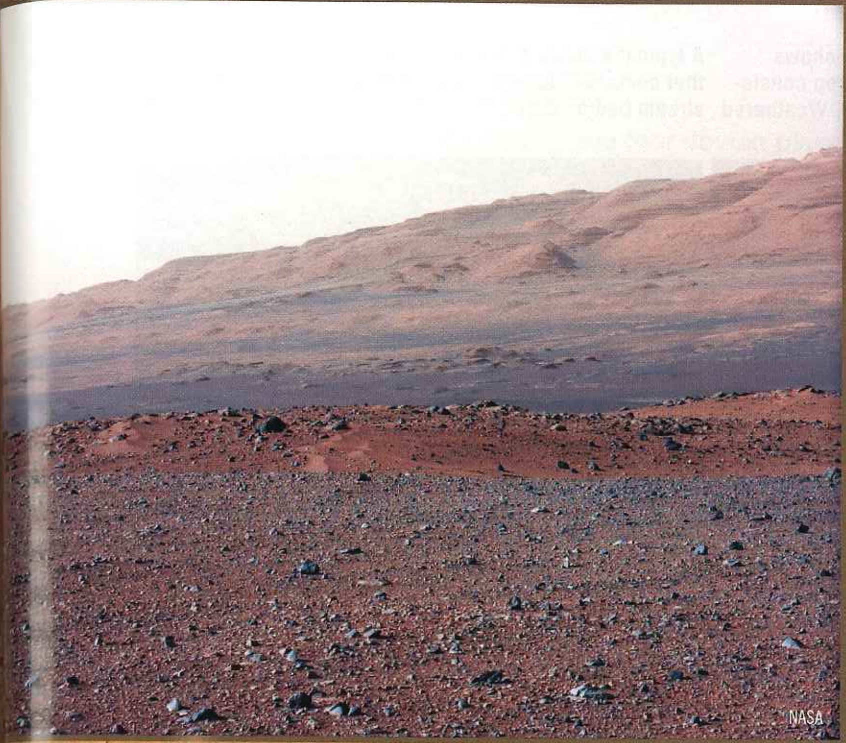
MARS LANDING SITES

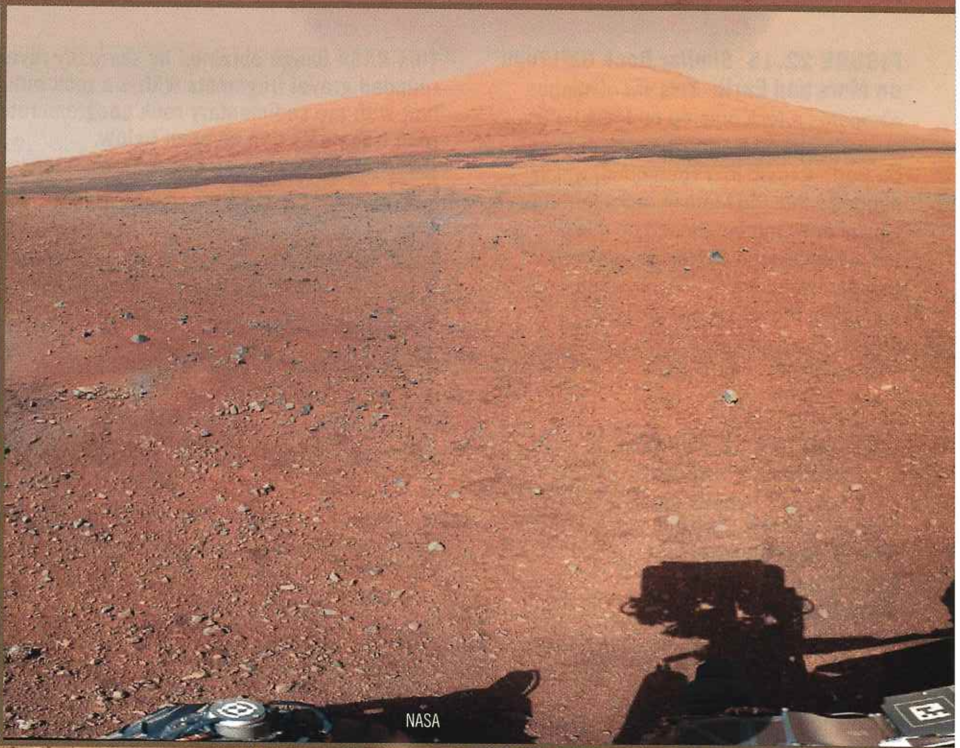
NASA

The U.S. has successfully landed seven rovers on the surface of Mars. The most recent was NASA's Curiosity, which landed in Gale Crater in August, 2012.

NASA's Curiosity rover, the size of a car, gracefully landed on Mars after decelerating from 13,000 miles per hour to a complete stop. The landing, described as "seven minutes of terror," began a two-year mission in and around Gale Crater to discover signs of past or present microbial life.

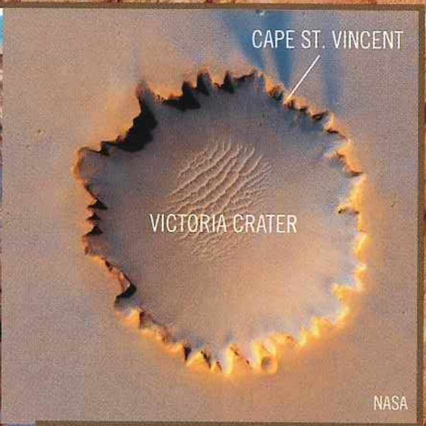
NASA





The layers in the background, located at the base of Mount Sharp, are thought to be surviving remnants of extensive deposits laid down in a lake long ago, or possibly wind-delivered sediments subsequently cemented together by ground water. Curiosity will use 10 instruments to investigate whether Mars had ever provided a water-rich environment.

This image captured by Curiosity shows Mount Sharp, a central peak located in the 96-mile wide Gale Crater.



This false-color image obtained by Rover Opportunity shows Cape St. Vincent, one of many promontories that jut out from the walls of Victoria Crater. Below the loose, jumbled rocks, layering in the crater walls shows evidence of ancient wind-blown dunes.

	Spacecraft	Type	Landed on Mars	Years Active**
1	Curiosity	Rover	August 2012	Remains in operation
2	Phoenix	Lander	May 2008	Ran out of power during its first Martian winter
3	Mars Reconnaissance	Orbiter	March 2006	Planned 2-year mission, remains in operation
4	Spirit	Rover	January 2004	Planned 4-year mission, operated for more than 6 years
5	Opportunity	Rover	January 2004	Planned 90-day mission, remains in operation
6	Odyssey	Orbiter	October 2001	Remains active, longest active spacecraft in orbit around another planet
7	Viking I	Lander*	July 1976	Operational for more than 6 years
8	Viking II	Lander*	September 1976	Operational for more than 3 years

* Also had an orbiter, ** As of late 2012

NASA

FIGURE 22.15 Similar Rock Outcrops on Mars and Earth This set of images compares a rock outcrop on Mars (left) with similar rocks on Earth. The rock outcrop on Earth formed in a streambed, which suggests that the Martian rocks formed in a similar environment. Based on this finding, the scientist John Grotzinger concluded that there was once "a vigorous flow on the surface of Mars." (Courtesy of NASA)

This NASA image obtained by *Curiosity* rover shows rounded gravel fragments within a rock outcrop consistent with the sedimentary rock conglomerate. Weathered rock fragments can be seen below.

A typical sample of the sedimentary rock conglomerate that contains rounded gravel fragments deposited in a stream bed on Earth.

FIGURE 22.16 Earth-like Stream Channels Are Strong Evidence That Mars Once Had Flowing Water Inset shows a close-up of a streamlined island where running water encountered resistant material along its channel. (Courtesy of NASA)

Most of the Martian landscape resembles Earth's rocky deserts, with abundant dunes and low areas partially filled with dust.

Water Ice on Mars Liquid water does not appear to exist anywhere on the Martian surface. However, poleward of about 30° latitude, ice can be found within 1 meter (3 feet) of the surface. In the polar regions, it forms small permanent ice caps. Current estimates place the maximum amount of water ice held by the Martian polar ice caps at about 1.5 times the amount covering Greenland.

Considerable evidence indicates that in the first 1 billion years of the planet's history, liquid water flowed on the surface, creating stream valleys and related features (**FIGURE 22.15**). One location where running water was involved in carving valleys can be seen in the *Mars Reconnaissance Orbiter* image in **FIGURE 22.16**. Notice the stream-like banks that contain numerous teardrop-shaped islands. These valleys appear to have been cut by catastrophic floods with discharge rates that were more than 1000 times greater than those of the Mississippi River. Most of these large flood channels emerge from areas of chaotic topography that appear to have formed when the surface collapsed. The most likely source of water for these flood-created valleys was the melting of subsurface ice. If the meltwater was trapped beneath a thick layer of permafrost, pressure could mount until a catastrophic release occurred. As the water escaped, the overlying surface would collapse, creating the chaotic terrain.

Not all Martian valleys appear to have resulted from water released in this manner. Some exhibit branching, tree-like patterns that resemble dendritic drainage networks on Earth. In addition, the *Opportunity* rover investigated structures similar to features created by water on Earth—including layered sedimentary rocks, playas (salt flats), and lake beds. Minerals that form only in the presence of water, such as hydrated sulfates, were also detected. Small spherical concretions of hematite, dubbed "blueberries," were found that probably precipitated from water to form lake sediments. Nevertheless, except in the polar regions, water does not appear to have significantly altered the topography of Mars for more than 1 billion years.

On August 6, 2012, the Mars rover *Curiosity* landed in Gale Crater, near what NASA calls Mount Sharp (officially known as Aeolis Mons). We can only imagine what *Curiosity* will uncover in its quest to study the habitability, climate, and geology of Mars.

22.3 CONCEPT CHECKS

1. What body in our solar system is most like Mercury?
2. Why are the surface temperatures so much higher on Venus than on Earth?
3. Venus was once referred to as "Earth's twin." How are these two planets similar? How do they differ from one another?
4. What surface features do Mars and Earth have in common?
5. Why are the largest volcanoes on Earth so much smaller than the largest ones on Mars?
6. What evidence suggests that Mars had an active hydrologic cycle in the past?

22.4 JOVIAN PLANETS

Compare and contrast the four Jovian planets.

The four Jovian (Jupiter-like) planets, in order from the Sun, are Jupiter, Saturn, Uranus, and Neptune. Because of their location within the solar system and their size and composition, they are also commonly called the *outer planets* and the *gas giants*.

Jupiter: Lord of the Heavens

The giant among planets, Jupiter has a mass 2.5 times greater than the combined mass of all other planets, satellites, and asteroids in the solar system. However, it pales in comparison to the Sun, with only 1/800 of the Sun's mass.

Jupiter orbits the Sun once every 12 Earth-years, and it rotates more rapidly than any other planet, completing one rotation in slightly less than 10 hours. When viewed telescopically, the effect of this fast spin is noticeable. The bulge of the equatorial region and the slight flattening at the poles are evident (see the Polar Flattening column in Table 22.1).

Jupiter's appearance is mainly attributable to the colors of light reflected from its three main cloud layers (**FIGURE 22.17**). The warmest, and lowest, layer is composed mainly of water ice and appears blue-gray; it is generally not seen in visible-light images. The middle layer, where temperatures are lower, consists of brown to orange-brown clouds of ammonium hydrosulfide droplets. These colors are thought to be by-products of chemical reactions occurring in Jupiter's atmosphere. Near the top of its atmosphere lie white wispy clouds of ammonia ice.

Because of its immense gravity, Jupiter is shrinking a few centimeters each year. This contraction generates most of the heat that drives Jupiter's atmospheric circulation. Thus, unlike winds on Earth, which are driven by solar energy, the heat emanating from Jupiter's interior produces the huge convection currents observed in its atmosphere.

Jupiter's convective flow produces alternating dark-colored *belts* and light-colored *zones*, as shown in Figure 22.17. The light clouds (*zones*) are regions where warm material is ascending and cooling, whereas the dark belts represent cool material that is sinking and warming. This convective circulation, along with Jupiter's rapid rotation, generates the high-speed, east–west flow observed between the belts and zones.

The largest storm on the planet is the Great Red Spot. This enormous anticyclonic storm that is twice the size of Earth has been known for 300 years. In addition to the Great Red Spot, there are various white and brown oval-shaped storms. The white ovals are the cold cloud tops of huge storms many times larger than hurricanes on Earth. The brown storm clouds reside at lower levels in the atmosphere. Lightning in various white oval storms has been photographed by the *Cassini* spacecraft, but the strikes appear to be less frequent than on Earth.

Jupiter's magnetic field, the strongest in the solar system, is probably generated by a rapidly rotating, liquid metallic hydrogen layer surrounding its core. Bright auroras, associated with the magnetic field, have been photographed over Jupiter's poles (**FIGURE 22.18**). Unlike Earth's auroras, which occur only in conjunction with heightened solar activity, Jupiter's auroras are continuous.

Jupiter's Moons Jupiter's satellite system, consisting of 67 moons discovered thus far, resembles a miniature solar system. Galileo discovered the four largest satellites, referred to as Galilean satellites, in 1610 (**FIGURE 22.19**). The two largest, Ganymede and Callisto, are roughly the size of Mercury, whereas the two smaller ones, Europa and Io, are about the size of Earth's Moon. The eight largest moons appear to have formed around Jupiter as the solar system condensed.

Jupiter also has many very small satellites (about 20 kilometers [12 miles] in diameter) that revolve in the opposite direction (*retrograde motion*) of the largest moons and have

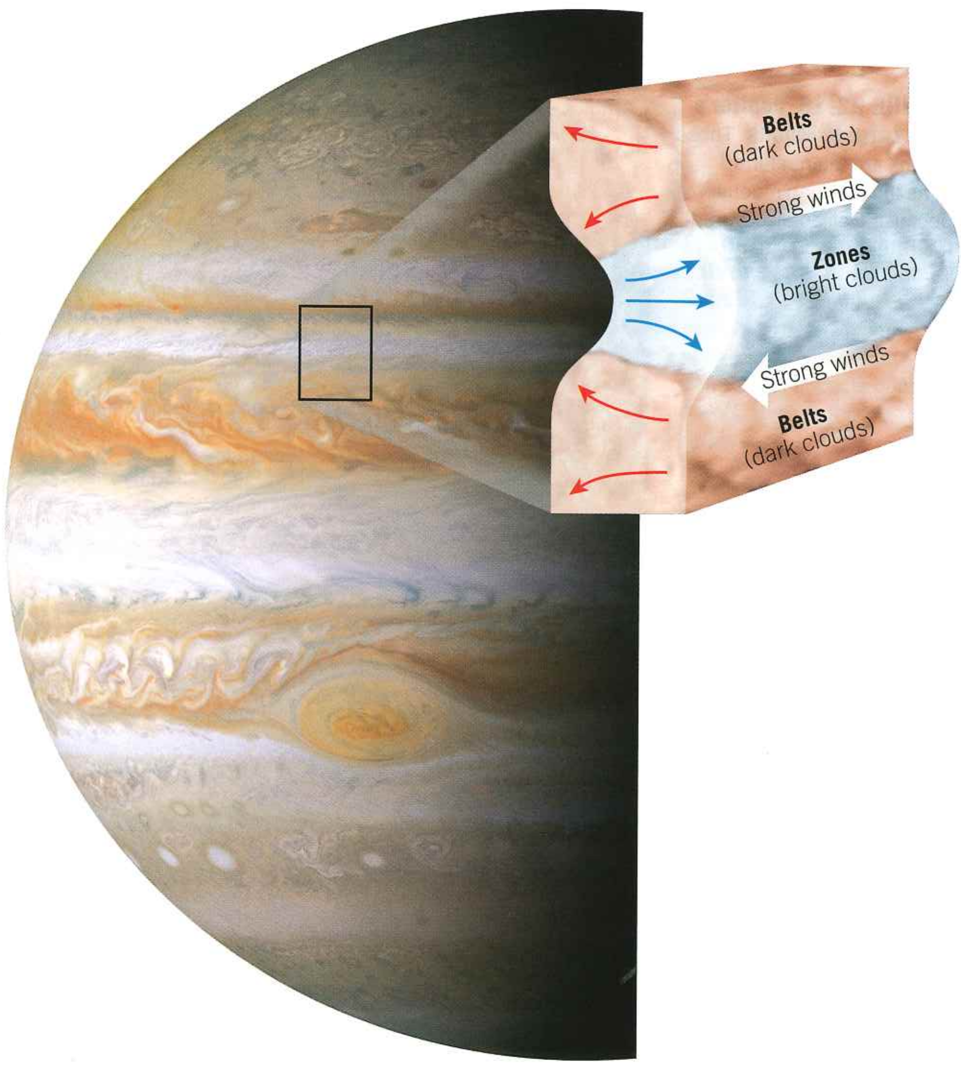


FIGURE 22.17 The Structure of Jupiter's Atmosphere The areas of light clouds (*zones*) are regions where gases are ascending and cooling. Sinking dominates the flow in the darker cloud layers (*belts*). This convective circulation, along with the rapid rotation of the planet, generates the high-speed winds observed between the belts and zones.

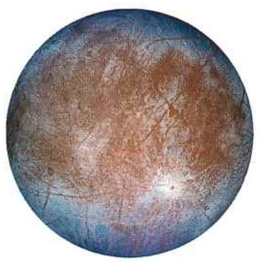
URE 22.18 View upiter's Aurora, en by the Hubble ce Telescope This omenon is produced by -energy electrons racing g Jupiter's magnetic The electrons excite ospheric gases and make n glow. (Courtesy of NASA/ Clark)

eccentric (elongated) orbits steeply inclined to the Jovian equator. These satellites appear to be asteroids or comets that passed near enough to be gravitationally captured by Jupiter or are remnants of the collisions of larger bodies.

The Galilean moons can be observed with binoculars or a small telescope and are interesting in their own right. Images from *Voyagers 1* and *2* revealed, to the surprise of most geoscientists, that each of the four Galilean satellites is a unique world (Figure 22.19). The *Galileo* mission also unexpectedly revealed that the composition of each satellite is strikingly different, implying a different evolution for each. For example, Ganymede has a dynamic core that generates a strong magnetic field not observed in other satellites.

URE 22.19 Jupiter's r Largest Moons These ons are often referred s the Galilean moons ause Galileo discovered m. (Courtesy of NASA)

A. Io is one of only three volcanically active bodies other than Earth known to exist in the solar system.

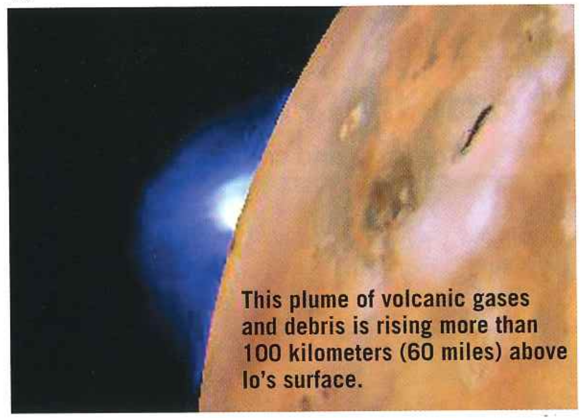


B. Europa, the smallest of the Galilean moons, has an icy surface that is crisscrossed by many linear features.

D. Callisto, the outermost of the Galilean satellites, is densely cratered, much like Earth's Moon

C. Ganymede, the largest Jovian satellite, exhibits cratered areas, smooth regions, and areas covered by numerous parallel grooves.

A.



B.

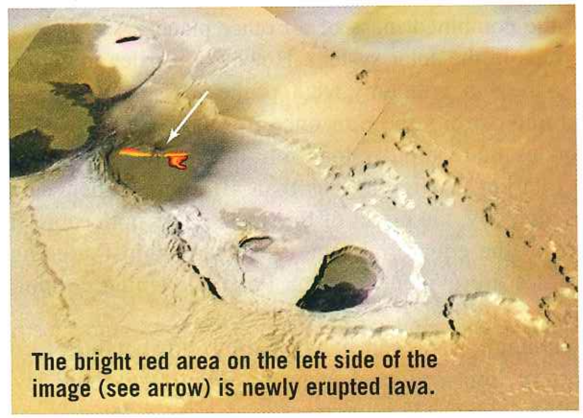


FIGURE 22.20 A Volcanic Eruption on Jupiter's Moon Io (Courtesy of NASA; Jet Propulsion Laboratory/University of Arizona/NASA)

The innermost of the Galilean moons, Io, is perhaps the most volcanically active body in our solar system. In all, more than 80 active, sulfurous volcanic centers have been discovered. Umbrella-shaped plumes have been observed rising from Io's surface to heights approaching 200 kilometers (125 miles) (**FIGURE 22.20A**). The heat source for volcanic activity is tidal energy generated by a relentless "tug of war" between Jupiter and the other Galilean satellites—with Io as the rope. The gravitational field of Jupiter and the other nearby satellites pull and push on Io's tidal bulge as its slightly eccentric orbit takes it alternately closer to and farther from Jupiter. This gravitational flexing of Io is transformed into heat (similar to the back-and-forth bending of a piece of sheet metal) and results in Io's spectacular sulfurous volcanic eruptions. Moreover, lava, thought to be mainly composed of silicate minerals, regularly erupts on its surface (**FIGURE 22.20B**).

The planets closer to the Sun than Earth are considered too warm to contain liquid water, and those farther from the Sun are generally too cold (although some features on Mars indicate that it probably had abundant liquid water at some point in its history). The best prospects of finding liquid water within our solar system lie beneath the icy surfaces of some of Jupiter's moons. For instance, an ocean of liquid water is possibly hidden under Europa's outer covering of ice. Detailed images from *Galileo* have revealed that Europa's icy surface is quite young and exhibits cracks apparently filled with dark fluid from below. This suggests that under its icy shell, Europa must have a warm, mobile interior—perhaps an ocean. Because

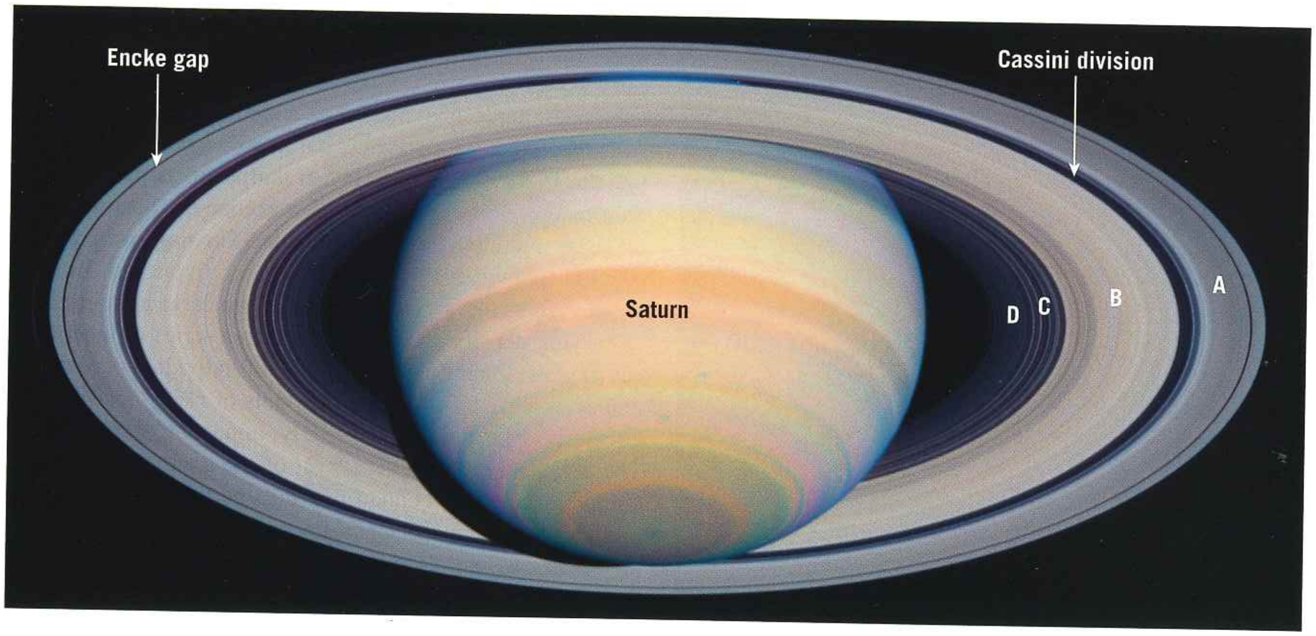


FIGURE 22.21 Saturn's Dynamic Ring System The two bright rings, called A ring (outer) and B ring (inner), are separated by the Cassini division. A second small gap (Encke gap) is also visible as a thin line in the outer portion of the A ring. (Courtesy of NASA)

liquid water is a necessity for life as we know it, there is considerable interest in sending an orbiter to Europa—and, eventually, a lander capable of launching a robotic submarine—to determine whether it harbors life.

Jupiter's Rings One of the surprising aspects of the *Voyager 1* mission was the discovery of Jupiter's ring system. More recently, the ring system was thoroughly investigated by the *Galileo* mission. By analyzing how these rings scatter light, researchers determined that the rings are composed of fine, dark particles that are similar in size to smoke particles. Furthermore, the faint nature of the rings indicates that these minute particles are widely dispersed. The main ring is composed of particles believed to be fragments blasted from the surfaces of Metis and Adrastea, two small moons of Jupiter. Impacts on Jupiter's moons Amalthea and Thebe are believed to be the source of the debris from which the outer gossamer ring formed.

Saturn: The Elegant Planet

Requiring more than 29 Earth-years to make one revolution, Saturn is almost twice as far from the Sun as Jupiter, yet their atmospheres, compositions, and internal structures are remarkably similar. The most striking feature of Saturn is its system of rings, first observed by Galileo in 1610 (**FIGURE 22.21**). Through his primitive telescope, the rings appeared as two small bodies adjacent to the planet. Their ring nature was determined 50 years later by Dutch astronomer Christian Huygens.

Saturn's atmosphere, like Jupiter's, is dynamic. Although the bands of clouds are fainter and wider near the equator, rotating "storms" similar to Jupiter's Great Red Spot occur in Saturn's atmosphere, as does intense lightning. Although the atmosphere is nearly 75 percent hydrogen and 25 percent helium, the clouds (or condensed gases) are composed of ammonia, ammonia hydrosulfide, and water, each segregated by temperature. Like Jupiter, the atmosphere's dynamics are driven by the heat released by gravitational compression.

Saturn's Moons The Saturnian satellite system consists of 62 known moons, of which 53 have been named. The moons vary significantly in size, shape, surface age, and origin. Twenty-three of the moons are "original" satellites that formed in tandem with their parent planet. At least three (Rhea, Dione, and Tethys) show evidence of tectonic activity, where internal forces have ripped apart their icy surfaces. Others, like Hyperion, are so porous that impacts punch into their surfaces (**FIGURE 22.22**). Many of Saturn's smallest moons have irregular shapes and are only a few tens of kilometers in diameter.

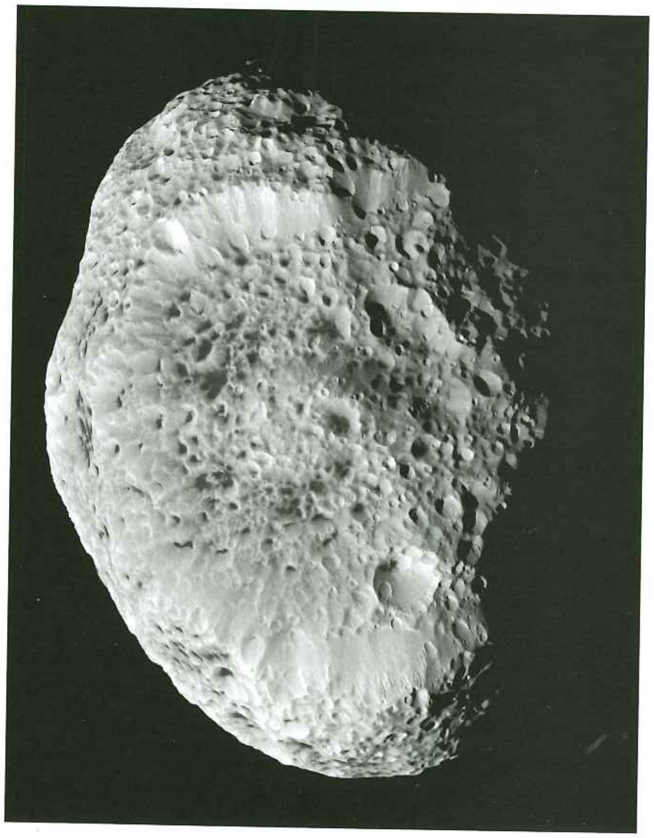


FIGURE 22.22 Hyperion, Saturn's Impact-Pummeled Satellite Planetary geologists think Hyperion's surface is so weak and porous that impacts punch into its surface. (Courtesy of NASA)

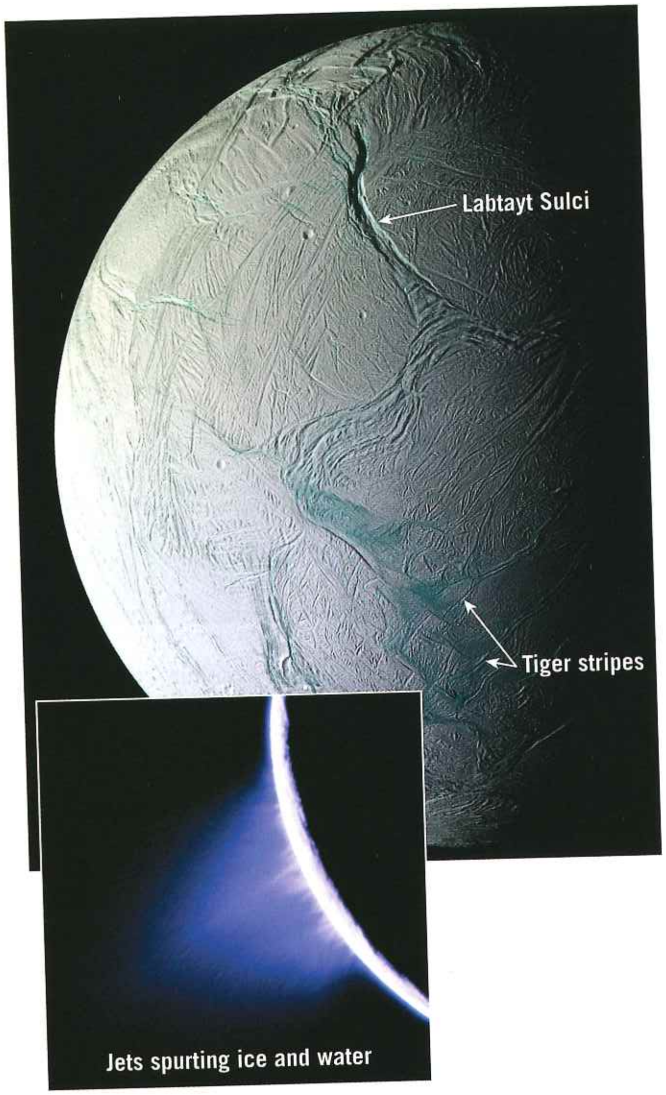


FIGURE 22.23 Enceladus, Saturn's Tectonically Active, Icy Satellite The Northern Hemisphere contains a 1-kilometer-deep (0.6 mile) chasm, and linear features, called tiger stripes, are visible in the lower right. Inset image shows jets spurting ice particles, water vapor, and organic compounds from the area of the tiger stripes. (Courtesy of NASA)

Saturn's largest moon, Titan, is larger than Mercury and is the second-largest satellite in the solar system. Titan and Neptune's Triton are the only satellites in the solar system known to have substantial atmospheres. Titan was visited and photographed by the *Cassini-Huygens* probe in 2005. The atmospheric pressure at Titan's surface is about 1.5 times that at Earth's surface, and the atmospheric composition is about 98 percent nitrogen and 2 percent methane, with trace organic compounds. Titan has Earth-like geologic landforms and geologic processes, such as dune formation and stream-like erosion caused by methane "rain." In addition, the northern latitudes appear to have lakes of liquid methane.

Enceladus is another unique satellite of Saturn—one of the few where active eruptions have been observed (**FIGURE 22.23**). The outgassing, comprised mostly of water, is thought to be the source that replenishes the material in Saturn's E ring. The volcanic-like activity occurs in areas called "tiger stripes" that consists of four large fractures with ridges on either side.

Saturn's Ring System In the early 1980s, the nuclear-powered *Voyagers 1* and *2* explored Saturn within 160,000 kilometers (100,000 miles) of its surface. More information was collected about Saturn in that short time than had been acquired since Galileo first viewed this "elegant planet" in the early 1600s. More recently, observations from ground-based telescopes, the Hubble Space Telescope, and the *Cassini-Huygens* spacecraft, have added to our knowledge of Saturn's ring system. In 1995 and 1996, when the positions of Earth and Saturn allowed the rings to be viewed edge-on, Saturn's faintest rings and satellites became visible. (The rings were visible edge-on again in 2009.)

Saturn's ring system is more like a large rotating disk of varying density and brightness than a series of independent ringlets. Each ring is composed of individual particles—mainly water ice, with lesser amounts of rocky debris—that circle the planet while regularly impacting one another. There are only a few gaps; most of the areas that look like empty space either contain fine dust particles or coated ice particles that are inefficient reflectors of light.

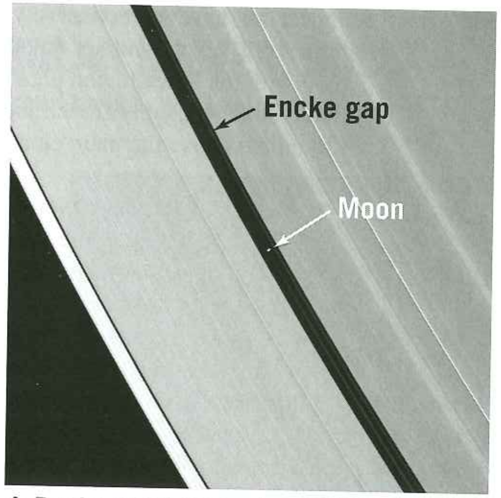
Most of Saturn's rings fall into one of two categories, based on density. Saturn's main (bright) rings, designated A and B, are tightly packed and contain particles that range in size from a few centimeters (pebble-size) to tens of meters (house-size), with most of the particles being roughly the size of a large snowball (see Figure 22.21). In the dense rings, particles collide frequently as they orbit the planet. Although Saturn's main rings (A and B) are 40,000 kilometers (25,000 miles) wide, they are very thin, only 10–30 meters (30–100 feet) from top to bottom.

At the other extreme are Saturn's faint rings. Saturn's outermost ring (E ring), not visible in Figure 22.21, is composed of widely dispersed, tiny particles. Recall that volcanic-like activity on Saturn's satellite Enceladus is thought to be the source of material for the E ring.

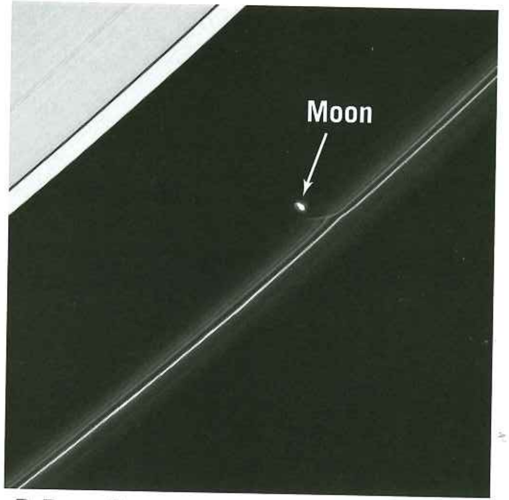
Studies have shown that the gravitational tugs of nearby moons tend to shepherd the ring particles by gravitationally altering their orbits (**FIGURE 22.24**). For example, the F ring, which is very narrow, appears to be the work of satellites located on either side that confine the ring by pulling back particles that try to escape. On the other hand, the Cassini division, a clearly visible gap in Figure 22.21, arises from the gravitational pull of Mimas, one of Saturn's moons.

Some of the ring particles are believed to be debris ejected from the moons embedded in them. It is also possible that material is continually recycled between the rings and the ring moons. The ring moons gradually sweep up particles, which are subsequently ejected by collisions with large chunks of ring material, or perhaps by energetic collisions with other moons. It seems, then, that planetary rings are not the timeless features that we once thought; rather, they are continually recycled.

The origin of planetary ring systems is still being debated. Perhaps the rings formed simultaneously and from the same material as the planets and moons—condensing from a flattened cloud of dust and gases that encircled the parent planet. Or perhaps the rings formed later, when a moon or large asteroid was gravitationally pulled apart after straying too close to a planet. Yet another hypothesis suggests that a foreign body collided catastrophically with one of the planet's moons, the fragments of which would tend to jostle one another and form a flat, thin ring. Researchers expect more light to be shed on the origin of planetary rings as the *Cassini* spacecraft continues its tour of Saturn.



A. Pan is a small moon about 30 kilometers in diameter that orbits in the Encke gap, located in the A ring. It is responsible for keeping the Encke gap open by sweeping up any stray material that may enter.



B. Prometheus, a potato-shaped moon, acts as a ring shepherd. Its gravity helps confine the moonlets in Saturn's thin Fring.

FIGURE 22.24 Two of Saturn's Ring Moons (Courtesy of NASA)

Uranus and Neptune: Twins

Although Earth and Venus have many similar traits, Uranus and Neptune are perhaps more deserving of being called "twins." They are nearly equal in diameter (both about four times the size of Earth), and they are both bluish in appearance, as a result of methane in their atmospheres. Their days are nearly the same length, and their cores are made of rocky silicates and iron—similar to the other gas giants. Their mantles, made mainly of water, ammonia, and methane, are thought to be very different from Jupiter and Saturn. One of the most pronounced differences between Uranus and Neptune is the time they take to complete one revolution around the Sun—84 and 165 Earth-years, respectively.

Uranus: The Sideways Planet Unique to Uranus is the orientation of its axis of rotation. Whereas the other planets resemble spinning toy tops as they circle the Sun, Uranus is like a top that has been knocked on its side but remains spinning (**FIGURE 22.25**). This unusual characteristic of Uranus is likely due to one or more impacts essentially knocking the planet sideways from its original orientation early in its evolution.

Uranus shows evidence of huge storm systems equivalent in size to those in the United States. Recent photographs from the Hubble Space Telescope also reveal banded clouds composed mainly of ammonia and methane ice—similar to the cloud systems of the other gas giants.

Uranus's Moons Spectacular views from *Voyager 2* showed that Uranus's five largest moons have varied terrains. Some have long, deep canyons and linear scars, whereas others possess large, smooth areas on otherwise crater-riddled surfaces. Studies conducted at California's Jet Propulsion Laboratory suggest that Miranda, the innermost of the five largest moons, was recently geologically active—most likely driven by gravitational heating, as occurs on Io.

Uranus's Rings A surprise discovery in 1977 showed that Uranus has a ring system. The discovery was made as Uranus passed in front of a distant star and blocked its view, a process called *occultation* (*occult* = *hidden*). Observers saw the star "wink" briefly five times (meaning five rings) before the primary occultation and again five times afterward. More recent ground- and space-based observations indicate that Uranus has at least 10 sharp-edged, distinct rings orbiting its equatorial region. Interspersed among these distinct structures are broad sheets of dust.

Neptune: The Windy Planet Because of Neptune's great distance from Earth, astronomers knew very little about

FIGURE 22.25 Uranus, Surrounded by Its Major Rings and a Few of Its Known Moons Also visible in this image are cloud patterns and several oval storm systems. This false-color image was generated from data obtained by Hubble's Near Infrared Camera. (Image by Hubble Space Telescope, courtesy of NASA)

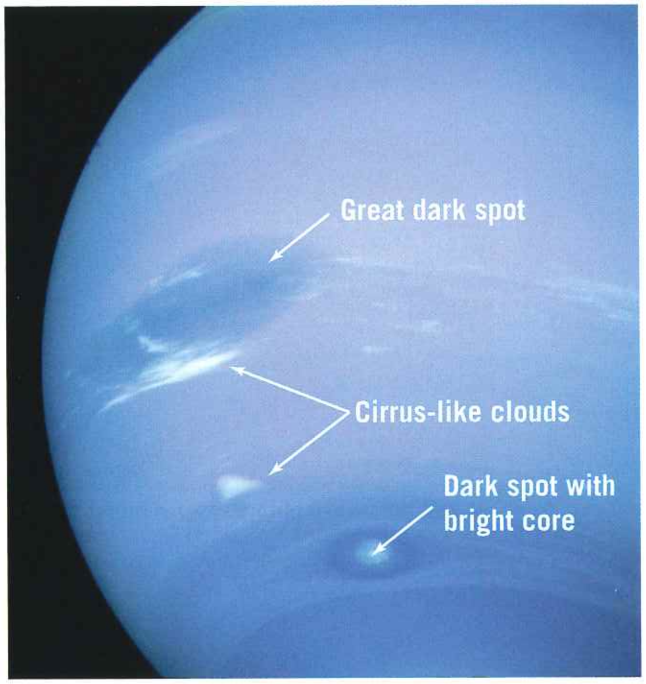


FIGURE 22.26 Neptune's Dynamic Atmosphere (Courtesy of NASA)

this planet until 1989. Twelve years and nearly 3 billion miles of *Voyager 2* travel provided investigators an amazing opportunity to view the outermost planet in the solar system.

Neptune has a dynamic atmosphere, much like that of the other Jovian planets (**FIGURE 22.26**). Record wind speeds exceeding 2400 kilometers (1500 miles) per hour encircle the planet, making Neptune one of the windiest places in the solar system. In addition, Neptune exhibits large dark spots thought to be rotating storms similar to Jupiter's Great Red Spot. However, Neptune's storms appear to have comparatively short life spans—usually only a few years. Another feature that Neptune has in common with the other Jovian planets is layers of white, cirrus-like clouds (probably frozen methane) about 50 kilometers (30 miles) above the main cloud deck.

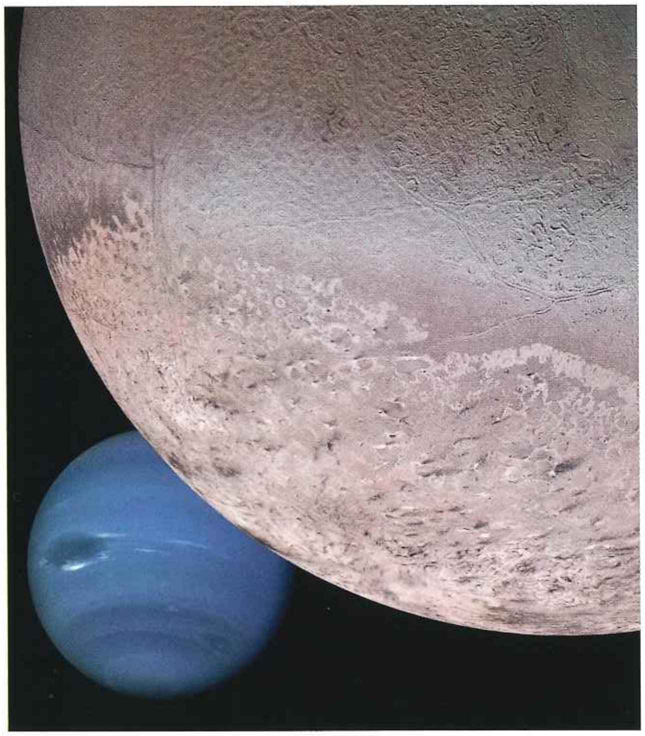


FIGURE 22.27 Triton, Neptune's Largest Moon The bottom of the image shows Triton's wind and sublimation-eroded south polar cap. Sublimation is the process whereby a solid (ice) changes directly to a gas. (Courtesy of NASA)

Neptune's Moons Neptune has 13 known satellites, the largest of which is the moon Triton; the remaining 12 are small, irregularly shaped bodies. Triton is the only large moon in the solar system that exhibits retrograde motion, indicating that it most likely formed independently and was later gravitationally captured by Neptune (**FIGURE 22.27**).

Triton and a few other icy moons erupt "fluid" ices—an amazing manifestation of volcanism. **Cryovolcanism** (from the Greek *kryos*, meaning "frost") describes the eruption of magmas derived from the partial melting of ice instead of silicate rocks. Triton's icy magma is a mixture of water ice, methane, and probably ammonia. When partially melted, this mixture behaves as molten rock does on Earth. In fact, upon reaching the surface, these magmas can generate quiet outpourings of ice lavas or occasionally produce explosive eruptions. An explosive eruptive column can generate the ice equivalent of volcanic ash. In 1989, *Voyager 2* detected active plumes on Triton that rose 8 kilometers (5 miles) above the surface and were blown downwind for more than 100 kilometers (60 miles). In other environments, ice lavas develop that can flow great distances from their source—similar to the fluid basaltic flows on Hawaii.

Neptune's Rings Neptune has five named rings; two of them are broad, and three are narrow, perhaps no more than 100 kilometers (60 miles) wide. The outermost ring appears to be partially confined by the satellite Galatea. Neptune's rings are most similar to Jupiter's in that they appear faint, which suggests that they are composed mostly of dust-size particles. Neptune's rings also display red colors, indicating that the dust is composed of organic compounds.

22.4 CONCEPT CHECKS

1. What is the nature of Jupiter's Great Red Spot?
2. Why are the Galilean satellites of Jupiter so named?
3. What is distinctive about Jupiter's satellite Io?
4. Why are many of Jupiter's small satellites thought to have been captured?
5. How are Jupiter and Saturn similar to one another?
6. What two roles do ring moons play in the nature of planetary ring systems?
7. How are Saturn's satellite Titan and Neptune's satellite Triton similar to one another?
8. Name three bodies in the solar system that exhibit active volcanism.

22.5 SMALL SOLAR SYSTEM BODIES

List and describe the principal characteristics of the small bodies that inhabit the solar system.

There are countless chunks of debris in the vast spaces separating the eight planets and in the outer reaches of the solar system. In 2006, the International Astronomical Union organized solar system objects not classified as planets or moons into two broad categories: (1) **small solar system bodies**, including *asteroids*, *comets*, and *meteoroids*, and (2) **dwarf planets**. The newest grouping, dwarf planets, includes Ceres, the largest known object in the asteroid belt, and Pluto, a former planet.

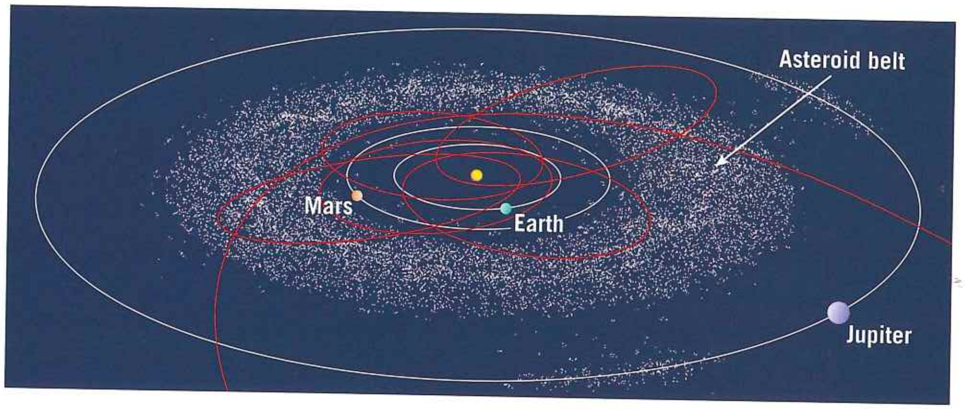


FIGURE 22.28 The Asteroid Belt The orbits of most asteroids lie between Mars and Jupiter. Also shown in red are the orbits of a few known near-Earth asteroids.

Asteroids and meteoroids are composed of rocky and/or metallic material with compositions somewhat like the terrestrial planets. They are distinguished according to size: Asteroids are larger than 100 meters (60 miles) in diameter, whereas meteoroids have diameters less than 100 meters. Comets, on the other hand, are loose collections of ices, dust, and small rocky particles that originate in the outer reaches of the solar system.

Asteroids: Leftover Planetesimals

Asteroids are small bodies (planetesimals) that remain from the formation of the solar system, which means they are about 4.6 billion years old. Most asteroids orbit the Sun between Mars and Jupiter, in the region known as the **asteroid belt** (**FIGURE 22.28**). Only five asteroids are more than 400 kilometers (250 miles) in diameter, but the solar system hosts an estimated 1 to 2 million asteroids larger than 1 kilometer (0.6 mile) and many millions that are smaller. Some travel along eccentric orbits that take them very near the Sun, and others regularly pass close to Earth and the Moon (Earth-crossing asteroids). Many of the recent large-impact craters on the Moon and Earth probably resulted from collisions with asteroids. There are an estimated 1000 to 2000 Earth-crossing asteroids that are more than 0.6 kilometer in diameter. Inevitably, Earth–asteroid collisions will occur again.

Because most asteroids have irregular shapes, planetary geologists initially speculated that they might be fragments of a broken planet that once orbited between Mars and Jupiter. However, the combined mass of all asteroids is now estimated to be only 1/1000 of the modest-sized Earth. Today, most researchers agree that asteroids are leftover debris from the solar nebula. Asteroids have lower densities than scientists originally thought, suggesting that they are porous bodies, like "piles of rubble," loosely bound together (**FIGURE 22.29**).

In February 2001, an American spacecraft became the first visitor to an asteroid. Although it was not designed for landing, *NEAR Shoemaker* landed successfully on Eros and collected information that has planetary geologists both intrigued and perplexed. Images obtained as the spacecraft drifted toward the surface of Eros revealed a barren, rocky surface composed of particles ranging in size from fine dust to boulders up to 10 meters (30 feet) across. Researchers unexpectedly discovered that fine debris tends to concentrate in the low areas, where it forms flat deposits resembling ponds. Surrounding the low areas, the landscape is marked by an abundance of large boulders.

One of several hypotheses to explain the boulder-strewn topography is seismic shaking, which would cause the boulders to move upward as the finer materials sink. This is analogous to what happens when a jar of sand and various-sized pebbles is shaken: The larger pebbles rise to the top, while the smaller sand grains settle to the bottom (sometimes referred to as the Brazil nut effect).

Indirect evidence from meteorites suggests that some asteroids might have been heated by a large impact event. A few large asteroids may have completely melted, causing

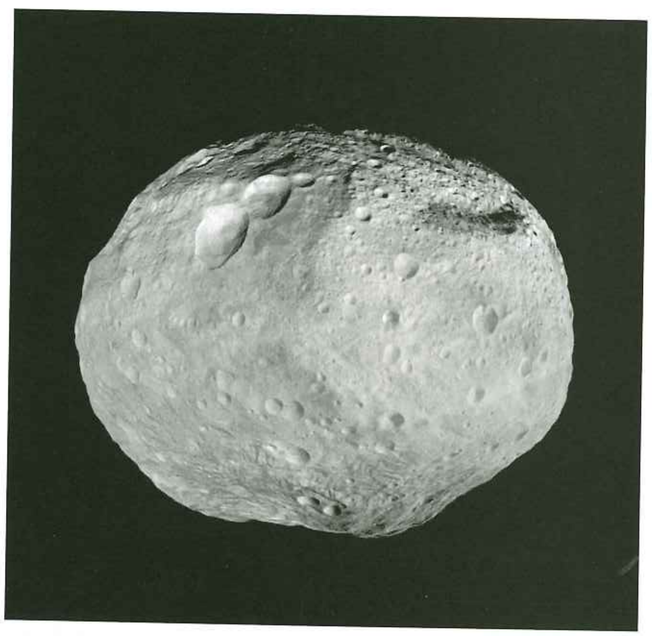


FIGURE 22.29 Giant Asteroid Vesta (Photo courtesy of NASA)

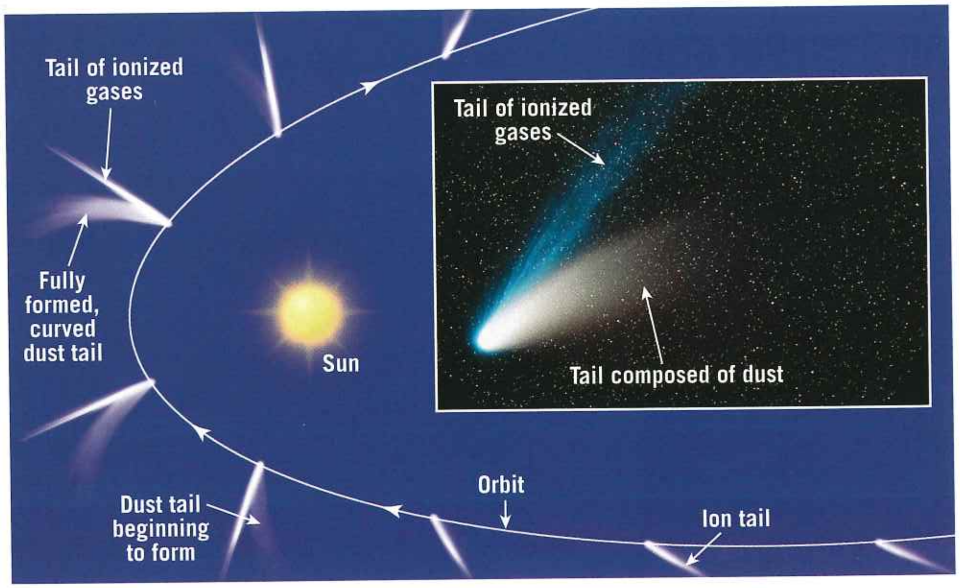


FIGURE 22.30 Changing Orientation of a Comet's Tail as It Orbits the Sun (Photo by Dan Schechter/Science Source)

them to differentiate into a dense iron core and a rocky mantle. In November 2005, the Japanese probe *Hayabusa* landed on a small near-Earth asteroid named 25143 Itokawa; it returned to Earth in June 2010. Analyzed samples suggest that the surface of the asteroid was identical in composition to meteorites and was once part of a larger asteroid. *Hayabusa 2* is scheduled to launch in 2014, to eventually expose subsurface samples by blasting a crater in asteroid 1999 JU3.

Comets: Dirty Snowballs

Comets, like asteroids, are leftover material from the formation of the solar system. They are loose collections of rocky material, dust, water ice, and frozen gases (ammonia, methane, and carbon dioxide), thus the nickname "dirty snowballs." Recent space missions to comets have shown their surfaces to be dry and dusty, which indicates that their ices are hidden beneath a rocky layer.

Most comets reside in the outer reaches of the solar system and take hundreds of thousands of years to complete a single orbit around the Sun. However, a smaller number of *short-period comets* (those having orbital periods of less than 200 years), such as the famous Halley's Comet, make regular encounters with the inner solar system (**FIGURE 22.30**). The shortest-period comet (Encke's Comet) orbits around the Sun once every 3 years.

FIGURE 22.31 Coma of Comet Holmes The nucleus of the comet is within the bright spot in the center. Comet Holmes, which orbits the Sun every six years, was uncharacteristically active during its most recent entry into the inner solar system. (Courtesy of NASA)

Structure and Composition of Comets

All the phenomena associated with comets come from a small central body called the **nucleus**. These structures are typically 1 to 10 kilometers in diameter, but nuclei 40 kilometers across have been observed. When comets reach the inner solar system, solar energy begins to vaporize their ices. The escaping gases carry dust from the comet's surface, producing a highly reflective halo called a **coma** (**FIGURE 22.31**). Within the coma, the small glowing nucleus with a diameter of only a few kilometers can sometimes be detected.

As comets approach the Sun, most develop tails that can extend for millions of kilometers. The tail of a comet points away from the Sun in a slightly curved manner (see Figure 22.30), which led early astronomers to believe that the Sun has a repulsive force that pushes away particles of the coma to form the tail. Scientists have identified two solar forces known to contribute to tail formation. One is *radiation pressure* caused by radiant energy (light) emitted by the Sun, and the second is the *solar wind*, a stream of charged particles ejected from the Sun. Sometimes a single tail composed of both dust and ionized gases is produced, but two tails are often observed (see Figure 22.30). The heavier dust particles produce a slightly curved tail that follows the comet's orbit, whereas the extremely light ionized gases are "pushed" directly away from the Sun, forming the second tail.

As a comet's orbit carries it away from the Sun, the gases forming the coma recondense, the tail disappears, and the comet returns to cold storage. Material that was blown from the coma to form the tail is lost forever. When all the gases are expelled, the inactive comet, which closely resembles an asteroid, continues its orbit without a coma or tail. It is believed that few comets remain active for more than a few hundred close orbits of the Sun.

The very first samples from a comet's coma (Comet Wild 2) were returned to Earth in January 2006 by NASA's

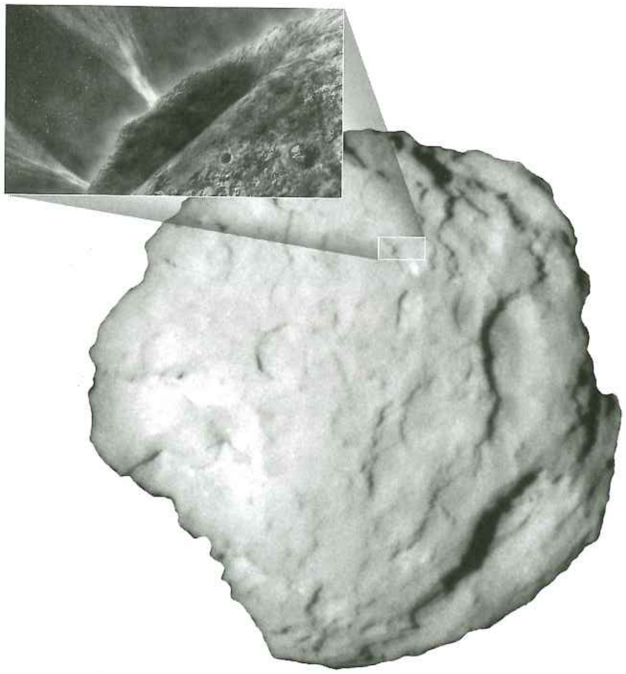


FIGURE 22.32 Comet Wild 2 This image shows Comet Wild 2, as seen by NASA's *Stardust* spacecraft. The inset shows an artist's depiction of jets of gas and dust erupting from Comet Wild 2. (Courtesy of NASA)

Stardust spacecraft (**FIGURE 22.32**). Images from *Stardust* show that the comet's surface was riddled with flat-bottomed depressions and appeared dry, although at least 10 gas jets were active. Laboratory studies revealed that the coma contained a wide range of organic compounds and substantial amounts of silicate crystals.

The Realm of Comets: The Kuiper Belt and Oort Cloud Most comets originate in one of two regions: the *Kuiper belt* or the *Oort cloud*. Named in honor of astronomer Gerald Kuiper, who predicted its existence, the **Kuiper belt** hosts comets that orbit in the outer solar system, beyond Neptune (see Figure 22.1). This disc-shaped structure is thought to contain about a billion objects over 1 kilometer in size. However, most comets are too small and too distant to be observed from Earth, even using the Hubble Space Telescope. Like the asteroids in the inner solar system, most Kuiper belt comets move in slightly elliptical orbits that lie roughly in the same plane as the planets. A chance collision between two Kuiper belt comets or the gravitational influence of one of the Jovian planets occasionally alters their orbits sufficiently to send them into our view.

Halley's Comet originated in the Kuiper belt. Its orbital period averages 76 years, and every one of its 29 appearances since 240 B.C. has been recorded, thanks to ancient Chinese astronomers—testimony to their dedication as astronomical observers and the endurance of Chinese culture. In 1910, Halley's Comet made a very close approach to Earth, making for a spectacular display.

Named for Dutch astronomer Jan Oort, the **Oort cloud** consists of comets that are distributed in all directions from the Sun, forming a spherical shell around the solar system. Most Oort cloud comets orbit the Sun at distances greater than 10,000 times the Earth–Sun distance. The gravitational effect of a distant passing star may send an occasional Oort cloud comet into a highly eccentric orbit that carries it toward the Sun. However, only a tiny fraction of Oort cloud comets have orbits that bring them into the inner solar system.

Meteoroids: Visitors to Earth

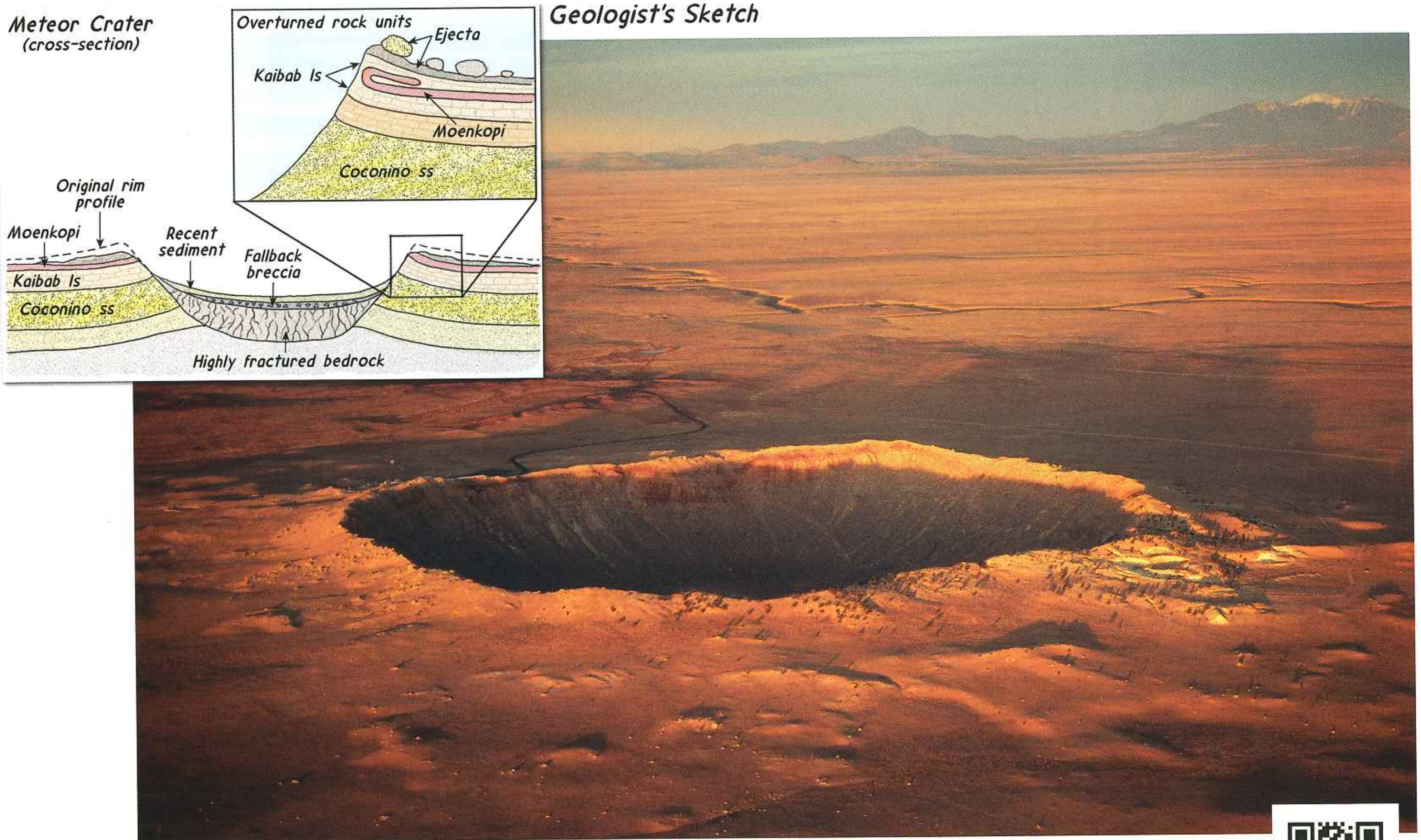
Nearly everyone has seen **meteors**, commonly (but inaccurately) called "shooting stars." These streaks of light can be observed in as little as the blink of an eye or can last as "long" as a few seconds. They occur when a small solid particle, a **meteoroid**, enters Earth's atmosphere from interplanetary space. Heat, created by friction between the meteoroid and the air, produces the light we see trailing across the sky. Most meteoroids originate from one of the following three sources: (1) interplanetary debris missed by the gravitational sweep of the planets during formation of the solar system, (2) material that is continually being ejected from the asteroid belt, or (3) the rocky and/or metallic remains of comets that once passed through Earth's orbit. A few meteoroids are probably fragments of the Moon, Mars, or possibly Mercury, ejected by a violent asteroid impact. Before *Apollo* astronauts brought Moon rocks back to Earth, meteorites were the only extraterrestrial materials that could be studied in the laboratory.

Meteoroids less than about 1 meter (3 feet) in diameter generally vaporize before reaching Earth's surface. Some, called *micrometeorites*, are so tiny and their rate of fall so slow that they drift to Earth continually as space dust. Researchers estimate that thousands of meteoroids enter Earth's atmosphere every day. After sunset on a clear, dark night, many are bright enough to be seen with the naked eye from Earth.

Meteor Showers Occasionally, meteor sightings increase dramatically to 60 or more per hour. These displays, called **meteor showers**, result when Earth encounters a swarm of meteoroids traveling in the same direction at nearly the same speed as Earth. The close association of these swarms to the orbits of some short-term comets strongly suggests that they represent material lost by these comets (**TABLE 22.2**). Some swarms, not associated with the orbits of known comets, are probably the scattered remains

TABLE 22.2 Major Meteor Showers

Shower	Approximate Dates	Associated Comet
Quadrantids	January 4–6	
Lyrids	April 20–23	Comet 1861 I
Eta Aquarids	May 3–5	Halley's Comet
Delta Aquarids	July 30	
Perseids	August 12	Comet 1862 III
Draconids	October 7–10	Comet Giacobini-Zinner
Orionids	October 20	Halley's Comet
Taurids	November 3–13	Comet Encke
Andromedids	November 14	Comet Biela
Leonids	November 18	Comet 1866 I
Geminids	December 4–16	



SmartFigure 22.33 Meteor Crater, Near Winslow, Arizona This cavity is about 1.2 kilometers (0.75 mile) across and 170 meters (560 feet) deep. The solar system is cluttered with asteroids and comets that can strike Earth with explosive force. (Photo by Michael Collier)

of the nucleus of a long-defunct comet. The notable *Perseid meteor shower* that occurs each year around August 12 is likely material ejected from the comet *Swift–Tuttle* on previous approaches to the Sun.

Most meteoroids large enough to survive passage through the atmosphere to impact Earth probably originate among the asteroids, where chance collisions or gravitational interactions with Jupiter modify their orbits and send them toward Earth. Earth's gravity does the rest.

A few very large meteoroids have blasted craters on Earth's surface that strongly resemble those on our Moon. At least 40 terrestrial craters exhibit features that could be produced only by an explosive impact of a large asteroid, or perhaps even a comet nucleus. More than 250 others may be of impact origin. Notable among them is Arizona's Meteor Crater, a huge cavity more than 1 kilometer (0.6 mile) wide and 170 meters (560 feet) deep, with an upturned rim that rises above the surrounding countryside (**FIGURE 22.33**). More than 30 tons of iron fragments have been found in the immediate area, but attempts to locate the main body have been unsuccessful. Based on the amount of erosion observed on the crater rim, the impact likely occurred within the past 50,000 years.

Types of Meteorites The remains of meteoroids, when found on Earth, are referred to as **meteorites** (**FIGURE 22.34**). Classified by their composition, meteorites are either (1) *irons*, mostly aggregates of iron with 5–20 percent nickel; (2) *stony* (also called *chondrites*), silicate minerals with inclusions of other minerals; or (3) *stony–irons*, mixtures of the two. Although stony meteorites are the most common, irons are found in large numbers because metallic meteorites withstand impacts better, weather more slowly, and are easily distinguished from terrestrial rocks. Iron meteorites are probably fragments of once-molten cores of large asteroids or small planets.

One type of stony meteorite, called a *carbonaceous chondrite*, contains organic compounds and occasionally simple amino acids, which are some of the basic building blocks of life. This discovery confirms similar findings in observational astronomy, which indicate that numerous organic compounds exist in interstellar space.

Data from meteorites have been used to ascertain the internal structure of Earth and the age of the solar system. If meteorites represent the composition of the terrestrial planets, as some planetary geologists suggest, our planet must contain a much larger percentage of iron than is indicated by surface rocks. This is one reason that geologists think Earth's core is mostly iron and nickel. In addition, radiometric dating of meteorites indicates that the age of our solar system is about 4.6 billion years. This "old age" has been confirmed by data obtained from lunar samples.

FIGURE 22.34 Iron Meteorite Found Near Meteor Crater, Arizona (Courtesy of M2 Photography/Alamy)

Dwarf Planets

Since its discovery in 1930, Pluto has been a mystery to astronomers who were searching for another planet in order to explain irregularities in Neptune's orbit. At the time of its discovery, Pluto was thought to be the size of Earth—too small to significantly alter Neptune's orbit. Later, estimates of Pluto's diameter, adjusted because of improved satellite images, indicated that it was less than half Earth's diameter. Then, in 1978, astronomers realized that Pluto appeared much larger than it really is because of the brightness of its newly discovered satellite, Charon (**FIGURE 22.35**). Most recently, calculations based on images obtained by the Hubble Space Telescope show that Pluto's diameter is 2300 kilometers (1430 miles), about one-fifth the diameter of Earth and less than half that of Mercury (long considered the solar system's "runt"). In fact, seven moons in the solar system, including Earth's, are larger than Pluto.

Even more attention was given to Pluto's status as a planet when astronomers discovered another large icy body in orbit beyond Neptune. Soon, more than 1000 of these *Kuiper belt objects* were discovered forming a band of objects—a second "asteroid belt," but located at the outskirts of the solar system. The Kuiper belt objects are rich in ices and have physical properties similar to those of comets. Many other planetary objects, some perhaps larger than Pluto, are thought to exist in this belt of icy worlds beyond Neptune's orbit. Researchers soon recognized that Pluto was unique among the planets—completely different from the four rocky, innermost planets, as well as the four gaseous giants.

In 2006, the International Astronomical Union, the group responsible for naming and classifying celestial objects, voted to designate a new class of solar system objects called *dwarf planets*. These are celestial bodies that orbit the Sun and are essentially spherical due to their own gravity but are not large enough to sweep their orbits clear of other debris. By this definition, Pluto is recognized as a dwarf planet and the prototype of this new category of planetary objects. Other

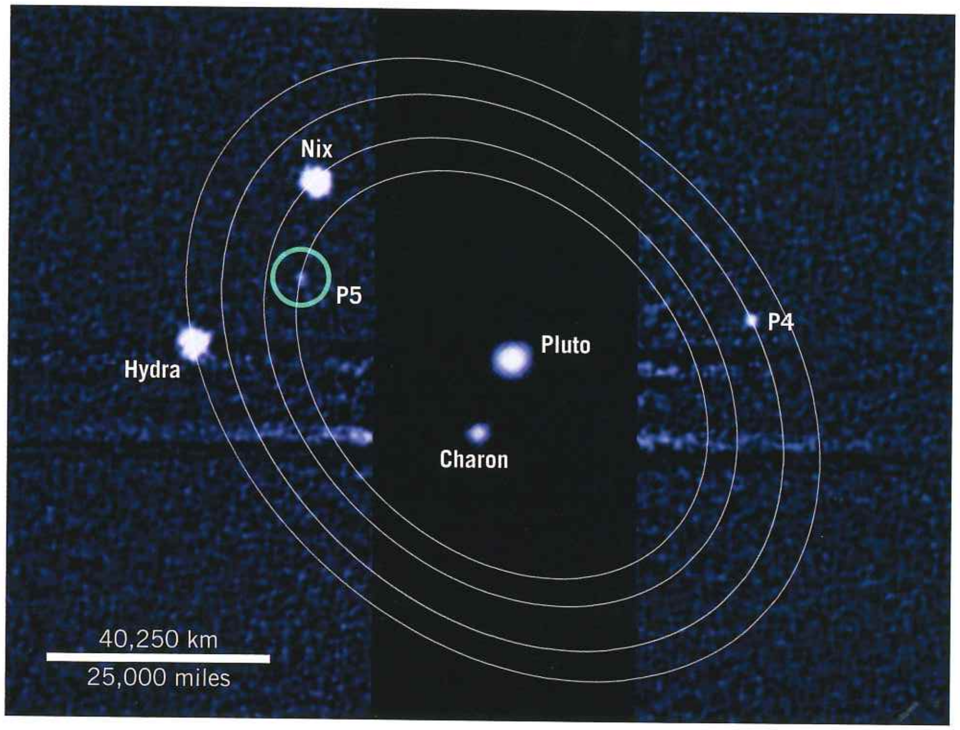


FIGURE 22.35 Pluto, with Its Five Known Moons (Courtesy of NASA)

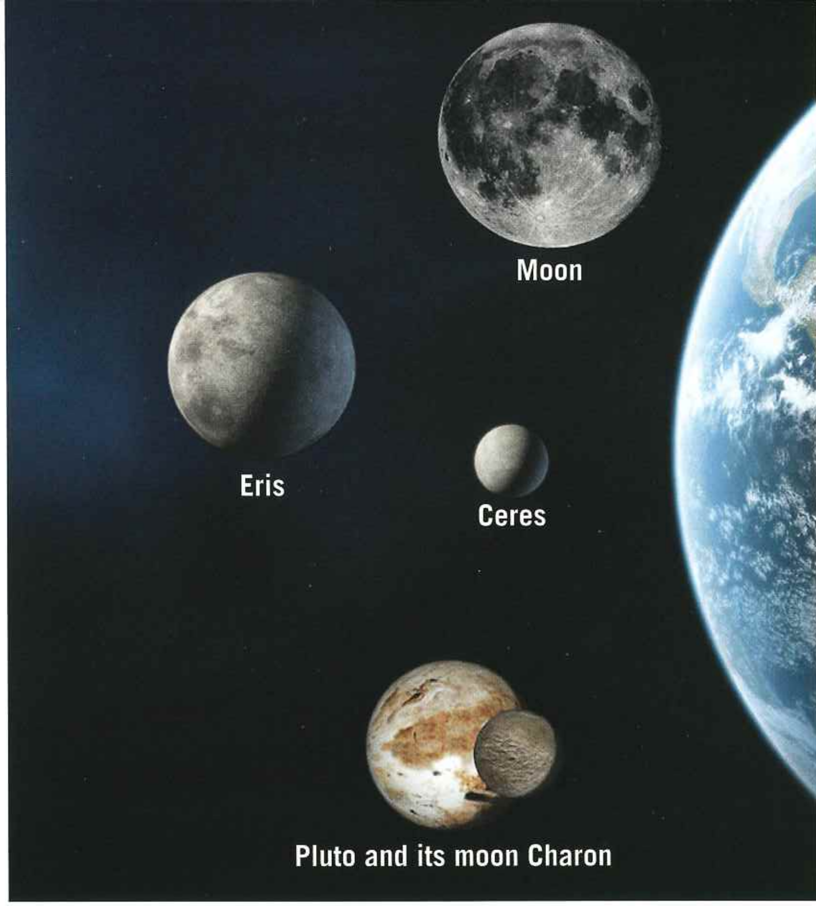


FIGURE 22.36 An Artist's Drawing Showing the Relative Sizes of the Best-Known Dwarf Planets Compared to Earth and Its Moon Eris, the largest known dwarf planet, has a very eccentric orbit that takes it as far as 100 AU from the Sun. Both Eris and Pluto are composed mainly of ices of water, methane, and ammonia. Ceres is the only identified dwarf planet in the asteroid belt. (Courtesy of NASA)

dwarf planets include Eris, a Kuiper belt object, and Ceres, the largest-known asteroid (**FIGURE 22.36**).

Pluto's reclassification was not the first such "demotion." In the mid-1800s, astronomy textbooks listed as many as 11 planets in our solar system, including the asteroids Vesta, Juno, Ceres, and Pallas. Astronomers continued to discover dozens of other "planets," a clear signal that these small bodies represent a class of objects separate from the planets.

The new classification will give a home to the hundreds of additional dwarf planets astronomers assume exist in the solar system. *New Horizons*, the first spacecraft designed to explore the outer solar system, was launched in January 2006. As of September 2012, *New Horizons* was halfway between the orbits of Uranus and Neptune. Scheduled to fly by Pluto in July 2015 and later explore the Kuiper belt, *New Horizons* carries tremendous potential for aiding researchers in further understanding the solar system.

22.5 CONCEPT CHECKS

1. Where are most asteroids found?
2. Compare and contrast asteroids and comets.
3. What do you think would happen if Earth passed through the tail of a comet?
4. Where are most comets thought to reside? What eventually becomes of comets that orbit close to the Sun?
5. Differentiate among the following solar system bodies: meteoroid, meteor, and meteorite.
6. What are the three main sources of meteoroids?
7. Why was Pluto demoted from the ranks of the officially recognized planets?

22 CONCEPTS IN REVIEW

Touring Our Solar System

22.1 OUR SOLAR SYSTEM: AN OVERVIEW

Describe the formation of the solar system according to the nebular theory. Compare and contrast the terrestrial and Jovian planets.

KEY TERMS: nebular theory, solar nebula, planetesimal, protoplanet, terrestrial (Earth-like) planet, Jovian (Jupiter-like) planet, escape velocity, impact crater

- Our Sun is the most massive body in a solar system, which includes planets, dwarf planets, moons, and other small bodies. The planets all orbit in the same direction and at speeds proportional to their distance from the Sun, with inner planets moving faster and outer planets moving more slowly.
- The solar system's formation is described by the nebular theory, which proposes that the system began as a solar nebula before condensing due to gravity. While most of the matter ended up in the Sun, some material formed a thick disc around the early Sun and later clumped together into larger and larger bodies. Planetesimals collided to form protoplanets, and protoplanets grew into planets.
- The four terrestrial planets are enriched in rocky materials, whereas the Jovian planets have a higher proportion of ice and gas. The terrestrial planets are relatively dense, with thin atmospheres, while the Jovian planets are less dense and have thick atmospheres.
- Smaller planets have less gravity to retain gases in their atmosphere. It's easier for lightweight gases such as hydrogen and helium to reach escape velocity in this situation, so the atmospheres of the terrestrial planets tend to be enriched in heavier gases, such as water vapor, carbon dioxide, and nitrogen.

22.2 EARTH'S MOON: A CHIP OFF THE OLD BLOCK

List and describe the major features of Earth's Moon and explain how maria basins were formed.

KEY TERMS: maria, lunar highlands (terrae), lunar regolith

- Earth's Moon is the largest moon relative to its planet, and its composition is unique in the solar system, approximately the same as the composition of Earth's mantle (density = 3.3 g/cm^3). The Moon likely formed due to a collision between a Mars-sized protoplanet and the early Earth. The bulk of the protoplanet's iron core material was incorporated into Earth, and its rocky mantle material spun off to make the Moon.
- Two types of topography dominate the lunar surface: (1) light-colored lunar highlands (or terrae) dominated by relatively old anorthosite breccia and (2) darker lowlands called maria, which are dominated by younger flood basalts. Both terrae and maria are partially covered by a layer called lunar regolith, which is produced by micrometeorite bombardment.

Q Briefly describe the formation of our Moon and how its formation accounts for its low density compared to that of Earth.

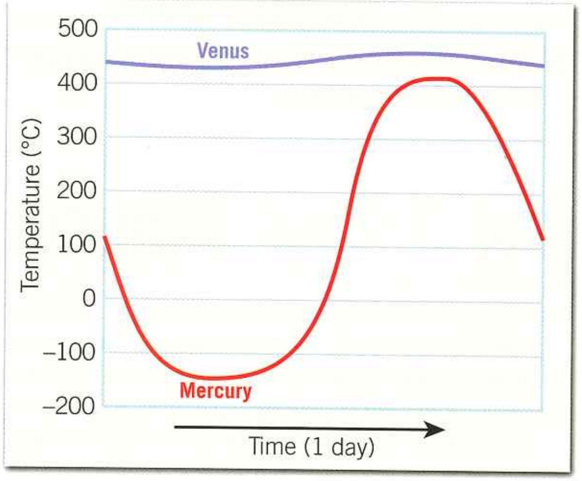
22.3 TERRESTRIAL PLANETS

Outline the principal characteristics of Mercury, Venus, and Mars. Describe their similarities to and differences from Earth.

- Mercury is the planet closest to the Sun. It has a very thin atmosphere and a weak magnetic field. Because it has a very thin atmosphere and its rate of rotation is extremely slow, the temperature on the surface varies from less than −173°C (−280°F) at night to 427°C (800°F) during daylight hours. The lobate scarps on Mercury's surface are likely the traces of thrust faults, which formed due to the planet's cooling and contraction.
- Venus, the second planet from the Sun, has a very dense atmosphere that is dominated by carbon dioxide. The resulting extreme greenhouse effect produces surface temperatures around 450°C (900°F). The topography of Venus has been resurfaced by active volcanism.
- Mars is the fourth planet from the Sun. It has about 1 percent as much atmosphere as Earth, so it is relatively cold (−140°C to 20°C [−220°F to 68°F]). Mars appears to be the closest planetary analogue to Earth, showing surface evidence of rifting, volcanism, and modification by flowing water. Volcanoes on Mars, such as Olympus Mons, are much bigger than volcanoes on Earth because of the lack of plate motion on Mars: The lava accumulates in a single cone rather than forming a long chain of cones, as exemplified by the Hawaiian islands.

Q As you can see from this graph, Mercury's temperature varies a lot from "day" to "night," but Venus's temperature is relatively constant "around the clock." Suggest a reason for this difference.

Idealized graph comparing the daily temperature variations on Venus and Mercury.



22.4 JOVIAN PLANETS

Compare and contrast the four Jovian planets.

KEY TERM: cryovolcanism

- Jupiter is the fifth planet from the Sun. It is very big—several times greater than the combined mass of everything else in the solar system except for the Sun. Convective flow among its three layers of clouds produces its characteristic banded appearance. Persistent, giant rotating storms exist between these bands. Many moons orbit Jupiter, including Io, which shows active volcanism, and Europa, which has an icy shell.
- Saturn is the sixth planet from the Sun. Like Jupiter, it is big, gaseous, and endowed with dozens of moons. Some of these moons show evidence of tectonics, while Titan has its own atmosphere. Saturn's well-developed rings are made of many particles of water ice and rocky debris.
- Uranus is the seventh planet from the Sun. Like its "twin" Neptune, it has a blue atmosphere dominated by methane, and its diameter is about four times greater than Earth's. Uranus rotates sideways relative to the plane of the solar system. It has a relatively thin ring system and at least five moons.
- Neptune, the eighth planet from the Sun, has an active atmosphere, with fierce wind speeds and giant storms. It has one large moon, Triton, which shows evidence of cryovolcanism, as well as a dozen smaller moons and a ring system.

Q Prepare and label a sketch comparing the typical characteristics of terrestrial planets and those of Jovian planets.

22.5 SMALL SOLAR SYSTEM BODIES

List and describe the principal characteristics of the small bodies that inhabit the solar system.

KEY TERMS: small solar system body, dwarf planet, asteroid, asteroid belt, comet, nucleus, coma, Kuiper belt, Oort cloud, meteor, meteoroid, meteor shower, meteorite

- Small solar system bodies include rocky asteroids and icy comets. Both are basically scraps left over from the formation of the solar system or fragments from later impacts.
- Most asteroids are concentrated in a wide belt between the orbits of Mars and Jupiter. Some are rocky, some are metallic, and some are basically "piles of rubble" loosely held together by their own weak gravity.
- Comets are dominated by ices, "dirtied" by rocky material and dust. They originate in either the Kuiper belt (a second "asteroid belt" beyond Neptune) or the Oort cloud (a spherical "shell" around the otherwise planar "disc" of the solar system). When the orbit of a comet brings it through the inner solar system, solar radiation (sunlight) causes its ices to begin to vaporize, generating the coma (gaseous envelope around the comet's nucleus) and its characteristic "tail."
- A meteoroid is debris that enters Earth's atmosphere, flaring briefly as a meteor before either burning up or striking Earth's surface to become a meteorite. Asteroids and material lost from comets as they travel through the inner solar system are the most common source of meteoroids.
- Dwarf planets include Ceres (located in the asteroid belt), the dwarf planet Pluto, and Eris, a Kuiper belt object. They are spherical bodies that orbit the Sun but are not massive enough to have cleared their orbits of debris.


Muellek Josef/Shutterstock; National Science Foundation; Jerry Schad/Science Source; NASA/JPL-Caltech/UCAL/MPS/DLR/IDA

Q Shown here are four small solar system bodies. Identify each and explain the differences among them.

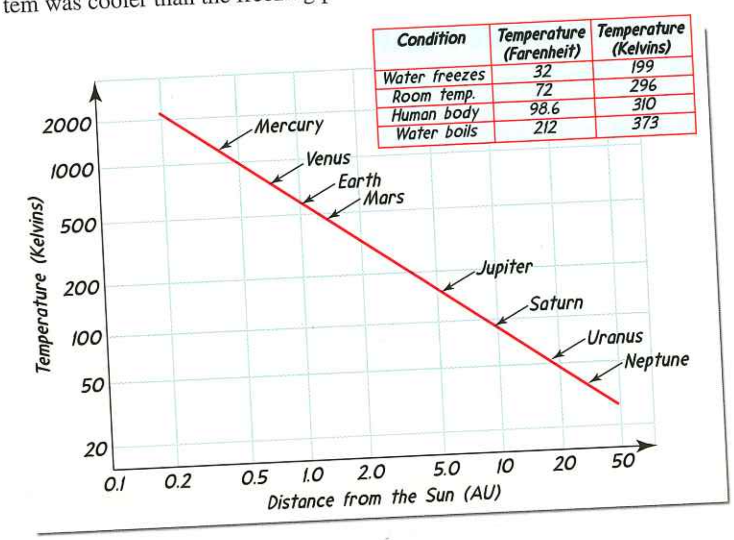
GIVE IT SOME THOUGHT

1. Assume that a solar system has been discovered in a nearby region of the Milky Way Galaxy. The accompanying table shows data that have been gathered about three of the planets orbiting the central star of this newly discovered solar system. Using Table 22.1 as a guide, classify each planet as either Jovian, terrestrial, or neither. Explain your reasoning.

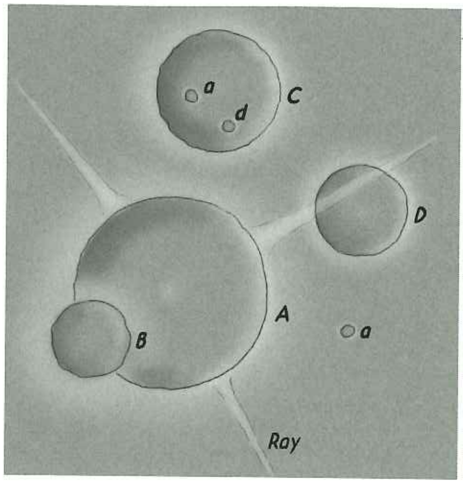
	Planet 1	Planet 2	Planet 3
Relative Mass (Earth = 1)	1.2	15	0.1
Diameter (km)	15,000	52,000	5000
Mean Distance from Star (AU)	1.4	17	35
Density (g/cm3)	4.8	1.22	5.3
Orbital Eccentricity	0.01	0.05	0.23

2. In order to conceptualize the size and scale of Earth and Moon as they relate to the solar system, complete the following:
   a. Approximately how many Moons (diameter 3475 kilometers [2160 miles]) would fit side-by-side across the diameter of Earth (diameter 12,756 kilometers [7926 miles])?
   b. Given that the Moon's orbital radius is 384,798 kilometers, approximately how many Earths would fit side-by-side between Earth and the Moon?
   c. Approximately how many Earths would fit side-by-side across the Sun, whose diameter is about 1,390,000 kilometers?
   d. Approximately how many Suns would fit side-by-side between Earth and the Sun, a distance of about 150,000,000 kilometers?

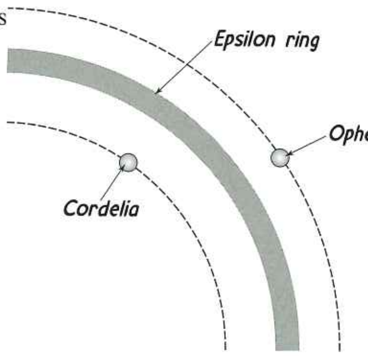
3. The accompanying graph shows the temperatures at various distances from the Sun during the formation of our solar system. Use it to complete the following:
   a. Which planets formed at locations where the temperature in the solar system was hotter than the boiling point of water?
   b. Which planets formed at locations where the temperature in the solar system was cooler than the freezing point of water?



4. The accompanying sketch shows four primary craters (A, B, C, and D). The impact that produced crater A produced two secondary craters (labeled "a") and three rays. Crater D has one secondary crater (labeled "d"). Rank the four primary craters from oldest to youngest and explain your ranking.

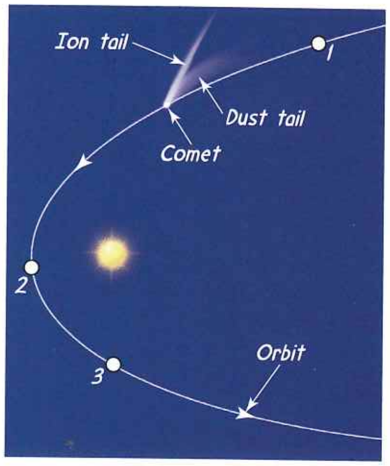


5. The accompanying diagram shows two of Uranus's moons, Ophelia and Cordelia, which act as shepherd moons for the Epsilon ring. Explain what would happen to the Epsilon ring if a large asteroid struck Ophelia, knocking it out of the Uranian system.



6. It has been estimated that Halley's Comet has a mass of 100 billion tons. Furthermore, it is estimated to lose about 100 million tons of material when its orbit brings it close to the Sun. With an orbital period of 76 years, calculate the maximum remaining life span of Halley's Comet.

7. The accompanying diagram shows a comet traveling toward the Sun at the first position where it has both an ion tail and a dust tail. Refer to this diagram to complete the following:
   a. For each of the three numbered sites, indicate whether the comet will have no tails, one tail, or two tails. If one tail or two tails are present, in what direction will they point?
   b. Would your answers to the preceding question change if the Sun's energy output were to increase significantly? If so, how would they change?
   c. If the solar wind suddenly ceased, how would this affect the comet and its tails?



8. Assume that three irregularly shaped planet-like objects, each smaller than our Moon, have just been discovered orbiting the Sun at a distance of 35 AU. One of your friends argues that the objects should be classified as planets because they are large and orbit the Sun. Another friend argues that the objects should be classified as dwarf planets, such as Pluto. State whether you agree or disagree with either or both of your friends. Explain your reasoning.

EXAMINING THE **EARTH SYSTEM**

1. On Earth the four major spheres (atmosphere, hydrosphere, geosphere, and biosphere) interact as a system with occasional influences from our near-space neighbors. Which of these spheres are absent, or nearly absent, on the Moon? Because the Moon lacks these spheres, list at least five processes that operate on Earth but are absent on the Moon.
2. Among the planets in our solar system, Earth is unique because water exists in all three states (solid, liquid, and gas) on and near its surface. In what state(s) of matter is water found on Mercury, Venus, and Mars?
   a. How would Earth's hydrologic cycle be different if its orbit were inside the orbit of Venus?
   b. How would Earth's hydrologic cycle be different if its orbit were outside the orbit of Mars?
3. If a large meteorite were to strike Earth in the near future, what effect might this event have on the atmosphere (in particular, on average temperatures and climate)? If these conditions persisted for several years, how might the changes influence the biosphere?

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