Planetary Geology*

CHAPTER

24

Panoramic view of the Martian landscape taken by the Spirit rover in 2004. (NASA/JPL/Cornell/Peter Arnold, Inc.)

*This chapter was revised by Teresa Tarbuck and Mark Watry, Rocky Mountain College.

When people first recognized that the planets resembled Earth more than the stars, excitement grew. Could intelligent life exist on these other planets, or elsewhere in the universe? Space exploration has rekindled this interest. So far, no evidence of extraterrestrial life within our solar system has emerged. Nevertheless, we study the other planets to learn about Earth's formation and early history. Recent space explorations have been organized with this goal in mind.

The Planets: An Overview

The Sun is the hub of a huge rotating system of eight classical planets, their satellites, and numerous smaller asteroids, comets, meteoroids, and dwarf planets. An estimated 99.85 percent of the mass of our solar system is contained within the Sun. The planets collectively make up most of the remaining 0.15 percent. The planets, traveling outward from the Sun, are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune (Figure 24.1). Pluto was recently reclassified as a dwarf planet.

Under the Sun's control, each planet is tethered by gravity in a nearly circular orbit—all of them traveling in the same direction. The nearest planet to the Sun, Mercury, has the fastest orbital motion, 48 kilometers 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 5 kilometers per second and requires 248 Earth-years to complete one revolution. Furthermore, the orbital planes of seven planets lie within 3 degrees of the plane of the Sun's equator. The other, Mercury, is inclined 7 degrees.

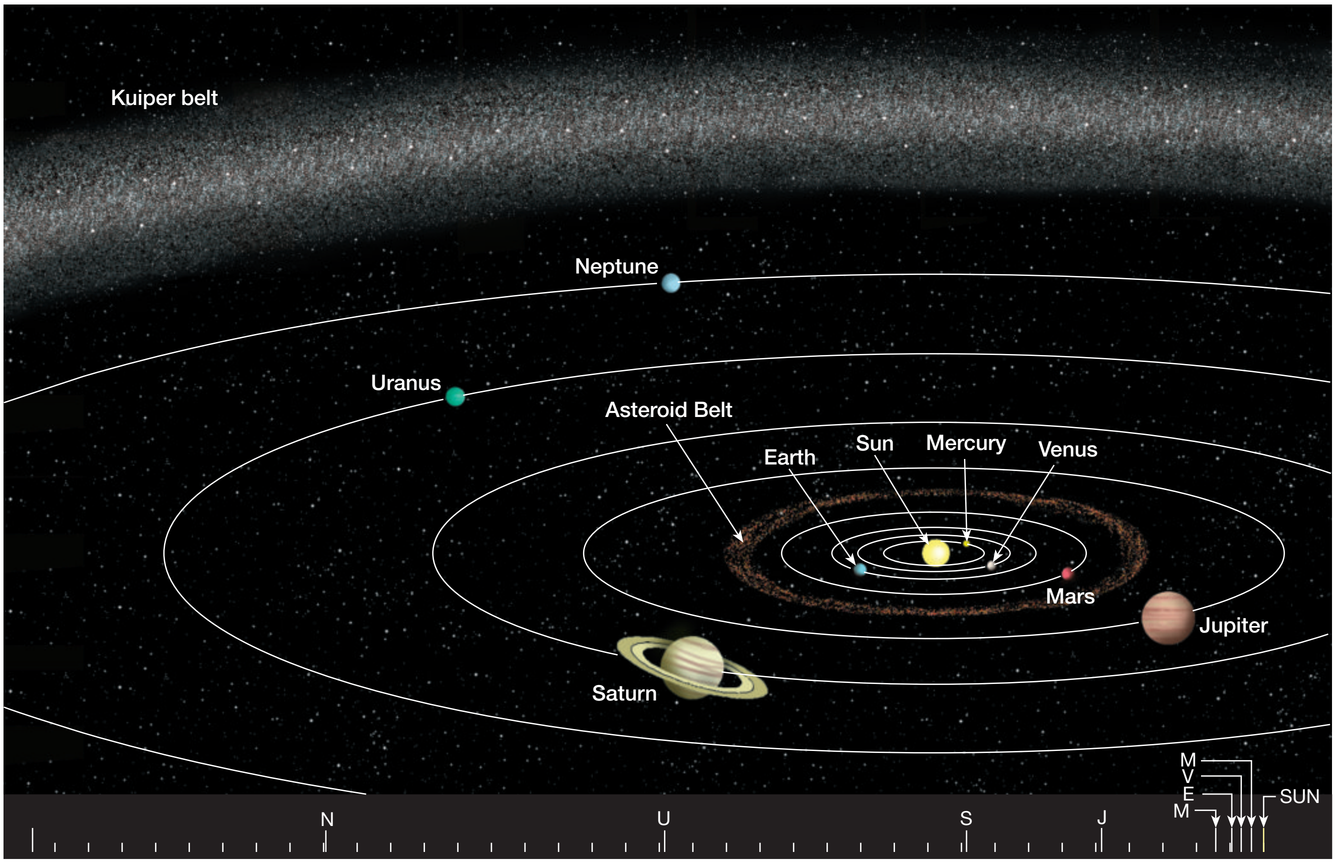


FIGURE 24.1 Orbits of the planets. Positions of the planets are shown to scale along bottom of diagram.

How Did the Planets Form?

The Sun and planets formed at the same time from a large rotating cloud of interstellar dust and gas called the **solar nebula.** As the solar nebula contracted, the vast majority of material collected in the center to form the hot *protosun.* The remainder formed a flattened, spinning disk. Within this spinning disk, matter gradually formed clumps of material that collided, stuck together and grew into asteroid-sized objects called **planetesimals.** The composition of these planetesimals depended largely on their location with respect to the protosun. (Temperatures were greater near the protosun and much lower in the outer reaches of the disk.) This was critical since only those materials that could condense—form solid or liquid clumps—in a particular location would be available to form planetesimals.

Near the present orbit of Mercury only metallic grains condensed—it was simply too hot for anything else to exist. Further out, near Earth's orbit, metallic as well as rocky substances condensed, and beyond Mars, ices of water, carbon dioxide, ammonia, and methane formed. It was from these clumps of matter that the planetesimals formed and through repeated collisions and accretion (sticking together) grew into eight **protoplanets** and their moons. It took roughly a billion years after the protoplanets formed to gravitationally sweep the solar system clear of interplanetary debris. This was a period of intense bombardment that is clearly visible on the Moon and elsewhere in the solar system. Only a small amount of the interplanetary matter escaped capture by a planet or moon and became the asteroids, comets, and meteoroids.

Terrestrial and Jovian Planets

Careful examination of Table 24.1 shows that the planets fall quite nicely into two groups: the **terrestrial** (Earth-like) **planets** (Mercury, Venus, Earth, and Mars), and the **Jovian** (Jupiter-like) **planets** (Jupiter, Saturn, Uranus, and Neptune). Pluto was recently demoted to a *dwarf planet*—a new class of solar system objects that have an orbit around the Sun but share their space with other celestial bodies. We will consider the nature of dwarf planets later in the chapter.

The most obvious difference between the terrestrial and the Jovian planets is their size (Figure 24.2). The largest terrestrial planets (Earth and Venus) have diameters only one-quarter as great as the diameter of the smallest Jovian planet (Neptune). Also, their masses are only 1/17 as great as Neptune's. Hence, the Jovian planets are often called *giants.* Because of their relative locations, the four Jovian planets are also referred to as the **outer planets,** whereas the terrestrial planets are called the **inner planets.** As we shall see, there appears to be a correlation between the location of these planets within the solar system and their sizes.

TABLE 24.1 Planetary Data

Planet	Symbol	Mean Distance from Sun: AU*	Mean Distance from Sun: Millions of Miles	Mean Distance from Sun: Millions of Kilometers	Period of Revolution	Inclination of Orbit	Orbital Velocity: mi/s	Orbital Velocity: 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	29.5^{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

Planet	Period of Rotation	Diameter: Miles	Diameter: Kilometers	Relative Mass (Earth = 1)	Average Density (g/cm³)	Polar Flattening (%)	Eccentricity†	Number of Known Satellites**
Mercury	59^d	3015	4878	0.06	5.4	0.0	0.206	0
Venus	244^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^h50^m	88,700	143,884	317.87	1.3	6.7	0.048	63
Saturn	10^h14^m	75,000	120,536	95.14	0.7	10.4	0.056	56
Uranus	17^h14^m	29,000	51,118	14.56	1.2	2.3	0.047	27
Neptune	16^h03^m	28,900	50,530	17.21	1.7	1.8	0.009	13

* AU = astronomical unit, Earth's mean distance from the Sun.
**Includes all satellites discovered as of August 2006.
† Eccentricity is a measure of the amount an orbit deviates from a circular shape. The larger the number, the less circular the orbit.

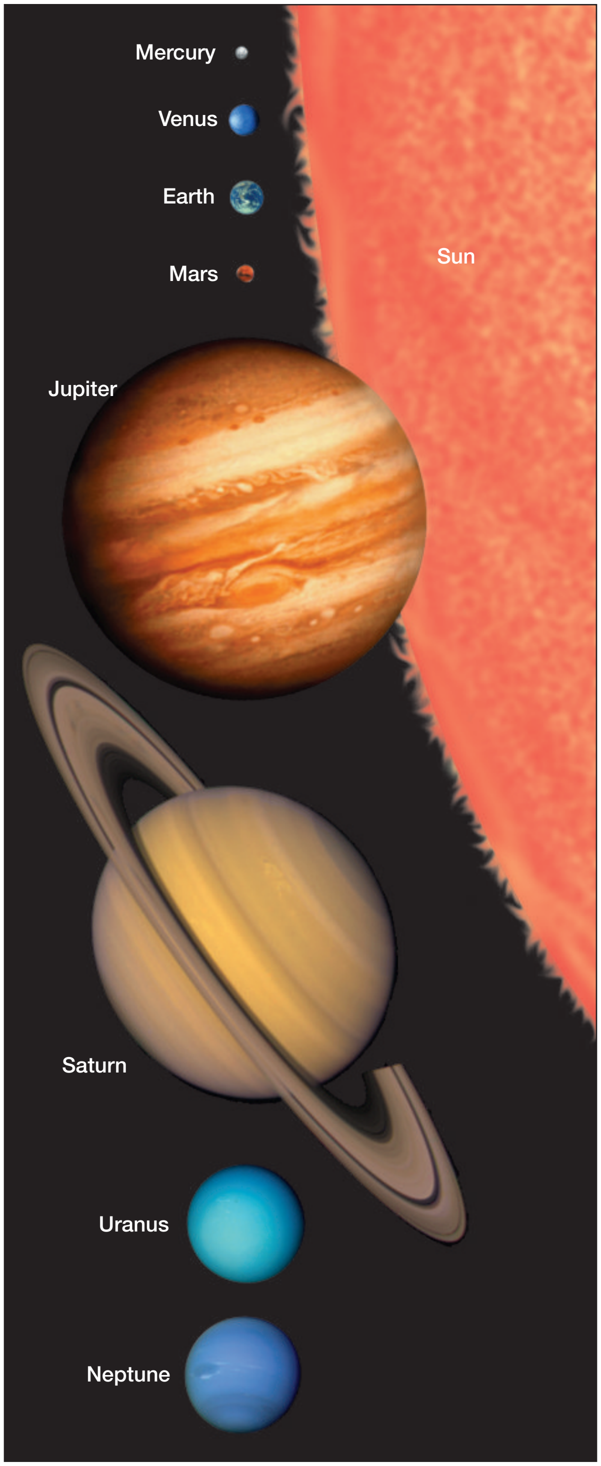


FIGURE 24.2 The planets drawn to scale.

Other dimensions in which the terrestrial and the Jovian planets differ include density, chemical makeup, and rate of rotation. The densities of the terrestrial planets average about five times the density of water, whereas the Jovian planets have densities that average only 1.5 times that of water. One of the outer planets, Saturn, has a density only 0.7 times that of water, which means that Saturn would float if placed in a large enough water tank! Differences in the chemical compositions of the planets are largely responsible for these density differences.

The Compositions of the Planets

The substances that make up the planets are divided into three compositional groups: *gases*, *rocks*, and *ices*, based on their melting points.

1. *Gases*, hydrogen and helium, are those with melting points near absolute zero (0 Kelvin). These two gases were the most abundant constituents of the solar nebula.
2. *Rocks* are principally silicate minerals and metallic iron, which have melting points that exceed 700°C.
3. *Ices* include ammonia, methane, carbon dioxide, and water. They have intermediate melting points (for example, water has a melting point of 0°C).

The terrestrial planets are dense, consisting mostly of rocky and metallic substances, with minor amounts of ices. The Jovian planets, on the other hand, contain large amounts of gases (hydrogen and helium) and ices (mostly water, ammonia, and methane). This accounts for their low densities. The Jovian planets also contain substantial amounts of rocky and metallic materials, which are concentrated in their central cores.

The Atmospheres of the Planets

The Jovian planets have very thick atmospheres of hydrogen, helium, methane, and ammonia. By contrast, the terrestrial planets, including Earth, have meager atmospheres at best. There are two reasons for this difference.

The first reason is the location of each planet within the solar nebula during its formation. The outer planets formed where the temperature was low enough to allow water vapor, ammonia, and methane to condense into ices. Hence, the Jovian planets contain large amounts of these volatiles. However, in the inner regions of the developing solar system the environment was too hot for ices to survive. Consequently, one of the long-standing questions for the nebular hypothesis was "How did Earth acquire water and other volatile gases?" The answer seems to be that during its protoplanet stage, Earth was bombarded with icy fragments (planetesimals) that originated beyond the orbit of Mars.

But why do Mercury and our Moon lack an atmosphere? Like the inner planets, they surely would have been bombarded by icy bodies. That brings us to the second reason that the inner planets (and the Moon) lack substantial atmospheres. A planet's ability to retain an atmosphere depends on its mass and its temperature. Simply stated, more massive planets have a better chance of retaining their atmospheres because atoms and molecules need a higher speed to escape. On the Moon the **escape velocity** is only 2.4 km/s compared with over 11 km/s for Earth.

Because of their strong gravitational fields, the Jovian planets have escape velocities that are much higher than

Students Sometimes Ask . . .

Why are the Jovian planets so much larger than the terrestrial planets?

According to the nebular hypothesis, the planets formed from a rotating disk of dust and gases that surrounded the Sun. The growth of planets began as solid bits of matter began to collide and clump together. In the inner solar system, the temperatures were so high that only metals and silicate minerals could form solid grains. It was too warm for ices of water, carbon dioxide, and methane to form. Thus, the innermost (terrestrial) planets grew mainly from the high melting point substances found in the solar nebula. By contrast, in the frigid outer reaches of the solar system, it was cold enough for clumps of water and other substances to form. Consequently, the outer planets grew not only from accumulations of solid bits of metals and silicate minerals but also from large quantities of ices. Eventually, the outer planets became large enough to gravitationally capture and hold onto even the lightest gases (hydrogen and helium), and thus grow to become "giant" planets.

that of Earth, which is the largest terrestrial planet. Consequently, it is much more difficult for gases to escape from the outer planets. Also, because the molecular motion of a gas is temperature-dependent, at the low temperatures of the Jovian planets even the lightest gases (hydrogen and helium) are unlikely to acquire the speed needed to escape.

By contrast, a comparatively warm body with a small surface gravity, such as Mercury and our Moon, is unable to hold even heavy gases such as carbon dioxide and radon. (Mercury does have trace amounts of gas present.) The slightly larger terrestrial planets of Earth, Venus, and Mars retain some heavy gases such as water vapor, nitrogen, and carbon dioxide, but even their atmospheres make up only a very small portion of their total mass.

Earth's Moon

Today Earth has hundreds of satellites, but only one, the Moon, is natural. Although other planets have moons, our planet-satellite system is unique in the solar system because Earth's Moon is unusually large compared to its parent planet. The diameter of the Moon is 3475 kilometers (2150 miles), about one-fourth of Earth's 12,756 kilometers (7920 miles).

From a calculation of the Moon's mass, its density is 3.3 times that of water. This density is comparable to that of *mantle* rocks on Earth but is considerably less than Earth's average density, which is 5.5 times that of water. Geologists have suggested that this difference can be accounted for if the Moon's iron core is small.

The gravitational attraction at the lunar surface is one-sixth of that experienced on Earth's surface (a 150-pound person on Earth weighs only 25 pounds on the Moon although they still have the same mass). 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 than on Earth.

The Lunar Surface

When Galileo first pointed his telescope toward the Moon, he saw two different types of terrain—dark lowlands and brighter, highly cratered highlands (Figure 24.3). Because the dark regions resembled seas on Earth, they were called **maria** (*mar* = sea, singular **mare**). Today we know that the maria are not oceans, but instead are flat plains that resulted from immense outpouring of fluid basaltic lavas. By contrast, the light-colored areas resemble Earth's continents, so the first observers dubbed them **terrae** (Latin for "land"). Today these areas are generally referred to as lunar **highlands,** because

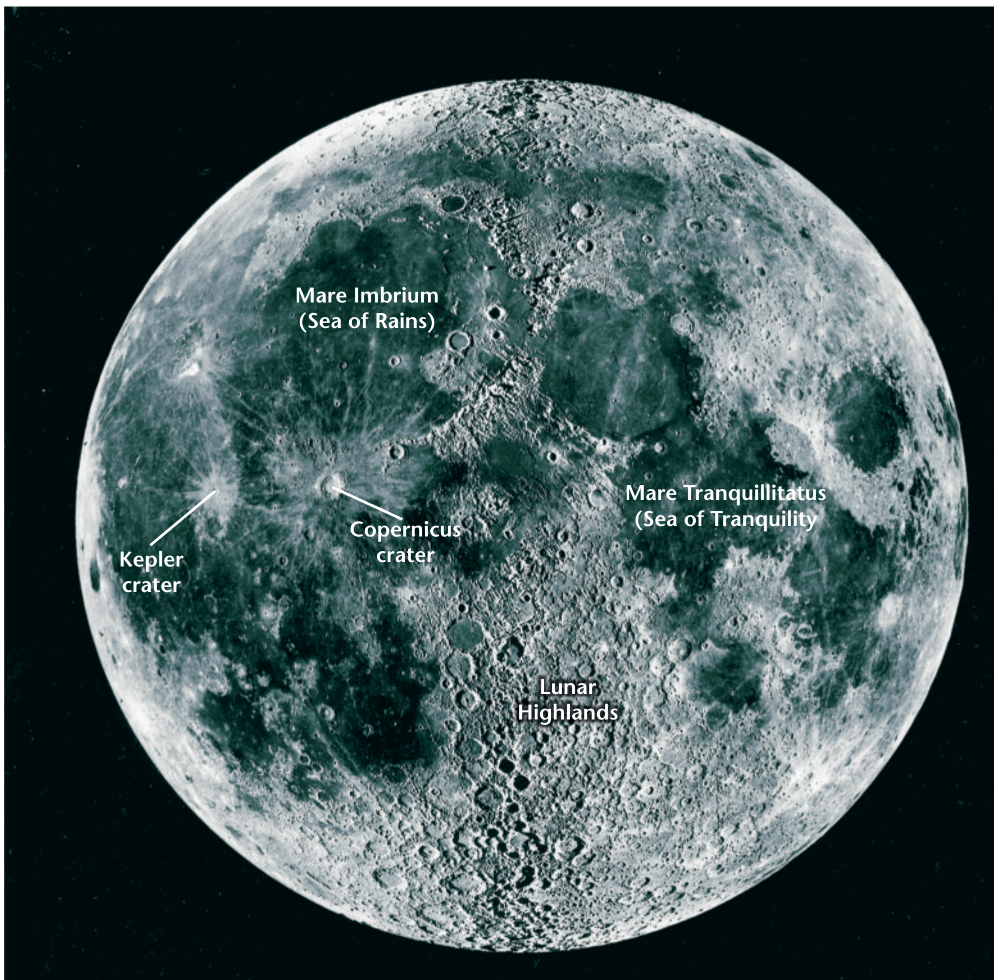


FIGURE 24.3 Telescopic view from Earth of the lunar surface. The major features are the dark "seas" (maria) and the light, highly cratered highlands. (UCO/Lick Observatory Image)

they are elevated several kilometers above the maria. Together the arrangement of terrae and maria result in the well-known "face of the moon."

Impact Craters The most obvious features of the lunar surface are craters. They are so profuse that craters-within-craters are the rule! The larger ones in the lower portion of Figure 24.3 are about 250 kilometers (150 miles) in diameter, roughly the width of Indiana. **Impact craters** are produced by the impact of rapidly moving debris (meteoroids, asteroids, and comets), a phenomenon that was considerably more common in the early history of the solar system than it is today.

By contrast, Earth has only about a dozen easily recognized impact craters. This difference can be attributed to Earth's atmosphere, erosion, and tectonic processes. Friction with the air burns up small debris and makes large meteoroids smaller before they reach the ground. In addition, evidence for most of the craters that formed in Earth's history has been obliterated by erosional or tectonic processes.

The formation of an impact crater is illustrated in Figure 24.4. Upon impact, the high-speed meteoroid compresses the material it strikes, then almost instantaneously the compressed rock rebounds, ejecting material from the crater. This process is analogous to the splash that occurs when a rock is dropped into water. Craters excavated by objects several kilometers across often exhibit a central peak, as seen in the large crater in Figure 24.5. Most of the ejected material (*ejecta*) lands in the crater or nearby, where it builds a rim around it. Depending on the size of the meteoroid, the heat generated by the impact may be sufficient to melt some of the impacted rock. Astronauts have brought back samples of glass beads produced in this manner, as well as rock formed when broken fragments and dust were welded together by the heat of an impact.

A meteoroid only 3 meters (10 feet) in diameter can blast out a 150-meter- (500-foot-) wide crater. A few of the large craters, such as Kepler and Copernicus, shown in Figure 24.3, formed from the bombardment of bodies 1 kilometer or more in diameter. These two large craters are thought to be relatively young because of the bright *rays* (splash marks) that radiate outward for hundreds of kilometers.

Highlands and "Seas" Densely pockmarked highland areas make up most of the lunar surface (Figure 24.6). In fact, most of the back side of the Moon is characterized by such topography. (Only astronauts have directly observed the farside, because the Moon rotates on its axis once with each revolution around Earth, always keeping the same side facing Earth.) As seen in Figure 24.3, highlands consist of an apparently endless sequence of overlapping craters. Indeed, the great number of impact craters is evidence of the Moon's violent early history. This activity crushed and repeatedly mixed at least the upper few kilometers of the lunar crust. As a result, the highlands are very rugged.

The highlands are made of plutonic rocks that contain over 90 percent plagioclase feldspar that rose like "scum" from a magma ocean early in lunar history. Maria, on the

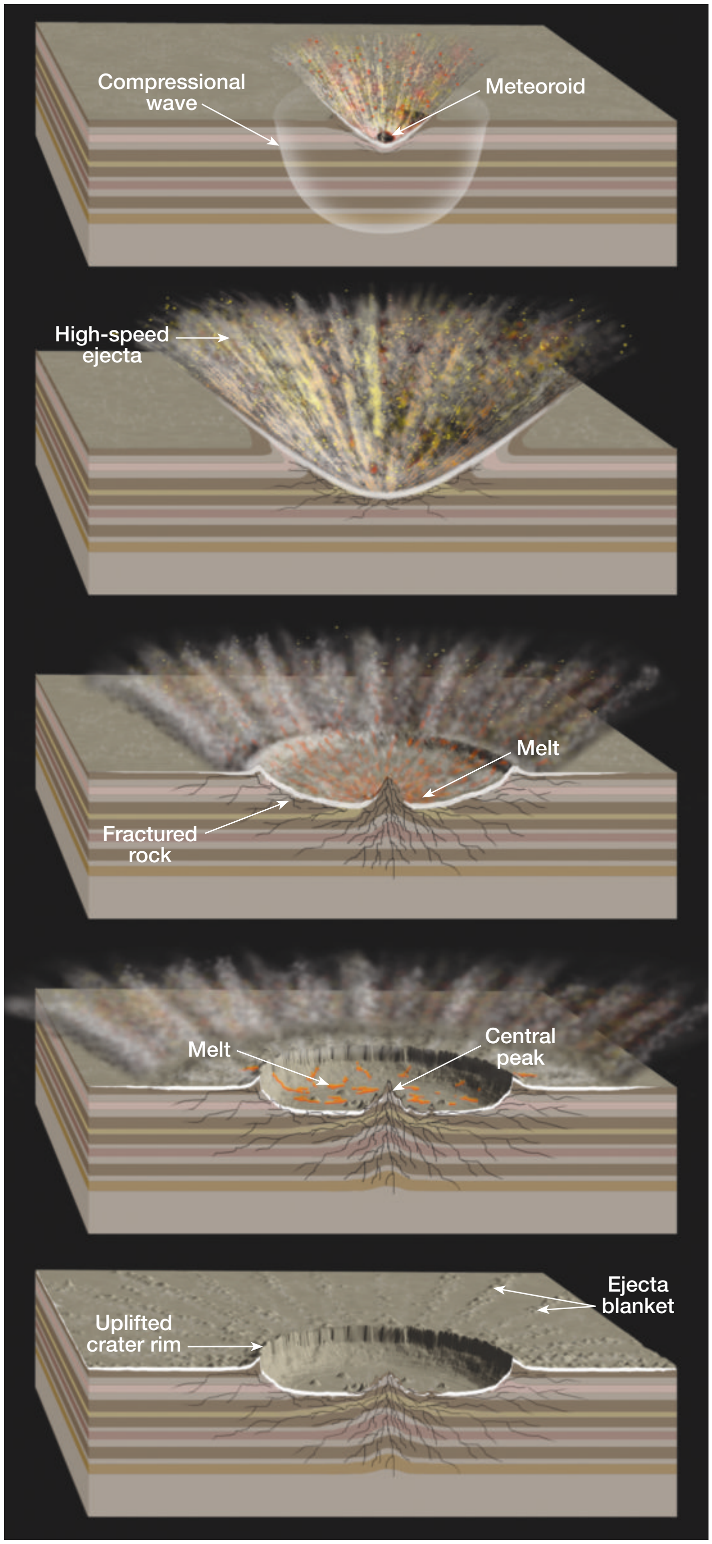


FIGURE 24.4 Formation of an impact crater. The energy of the rapidly moving meteoroid is transformed into heat energy and compressional waves. The rebound of the compressed rock causes debris to be ejected from the crater. Heat melts some material, producing glass beads. Small secondary craters are formed by the material "splashed" from the impact crater. (After E. M. Shoemaker)

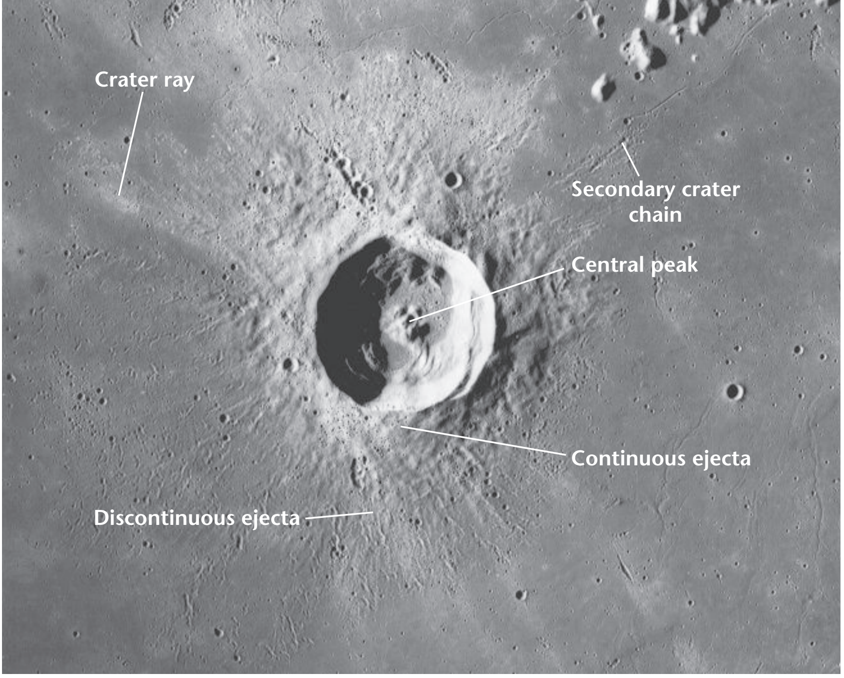


FIGURE 24.5 The 20-kilometer-wide lunar crater Euler in the southwestern part of Mare Imbrium. Clearly visible are the bright rays, central peak, secondary craters, and the large accumulation of ejecta near the crater rim. (Courtesy of NASA)

other hand, are composed of volcanic rocks with a mafic composition and, hence, are similar to flood basalts on Earth.

The dark, flat maria make up only about 16 percent of the Moon's landscape and are concentrated on the side of the Moon facing Earth. (Figure 24.3). More than 4 billion years ago, asteroids having diameters as large as Rhode Island excavated several huge craters on the lunar surface. Because the crust was sufficiently fractured, magma began to bleed out. Apparently the craters were flooded with layer upon layer of very fluid lavas resembling those of the Columbia Plateau in the Pacific Northwest (Figure 24.7). In most cases, these lavas welled up long after the craters formed. It seems that volcanism occurred because the crust was thinner and more fractured in these regions rather than because of heat generated by the impact itself.

Weathering and Erosion The Moon has no atmosphere or flowing water. Therefore, the processes of weathering and erosion that continually modify Earth's surface are virtually lacking on the Moon. In addition, tectonic forces are no longer active on the Moon, so earthquakes and volcanic eruptions do not occur. However, because the Moon is unprotected by an atmosphere, a different kind of erosion occurs: Tiny particles from space (micrometeorites) continually bombard its surface and ever so gradually smooth the landscape.

Both the maria and terrae are mantled with a layer of gray, unconsolidated debris derived from a few billion years of meteoric bombardment (Figure 24.8). This soil-like layer, properly called **lunar regolith** (*rhegos* = blanket, *lithos* = stone) is composed of igneous rocks, breccia, glass beads, and fine *lunar dust*. In the maria that have been explored by *Apollo* astronauts, the lunar regolith is apparently just over 3 meters (10 feet) thick.

Lunar History

Although the Moon is our nearest planetary neighbor and astronauts have sampled its surface, much is still unknown about its origin. The most widely favored scenario is that during the formative period of the solar system, a glancing collision occurred between a Mars-sized body and a youthful semi-molten Earth (Figure 24.9). (Collisions of this type were probably frequent events in the early solar system.) During such a catastrophic collision most of the ejected debris would have collected in an orbit around Earth. Gradually this debris coalesced to form the Moon. Computer simulations show that most of the ejected material would have come from the mantles of both the impacting object and Earth (Figure 24.9). (Recall that the mantle makes up 82 percent of Earth's volume.) Further, if the impacting object had an iron core, this dense material would eventually have been incorporated into Earth's core. The *impact theory* is consistent with the Moon's internal structure—the Moon has a large mantle and a small core.

Planetary geologists have also worked out the basic details of the Moon's later history. One method of dating topographic features on the lunar surface is to observe variations in crater density (quantity per unit area). The greater the crater density, the longer the feature must have existed. From such evidence, scientists conclude that the Moon evolved in four phases: (1) the formation of the original crust, (2) the lunar highlands, (3) the maria basins, and (4) the rayed craters.

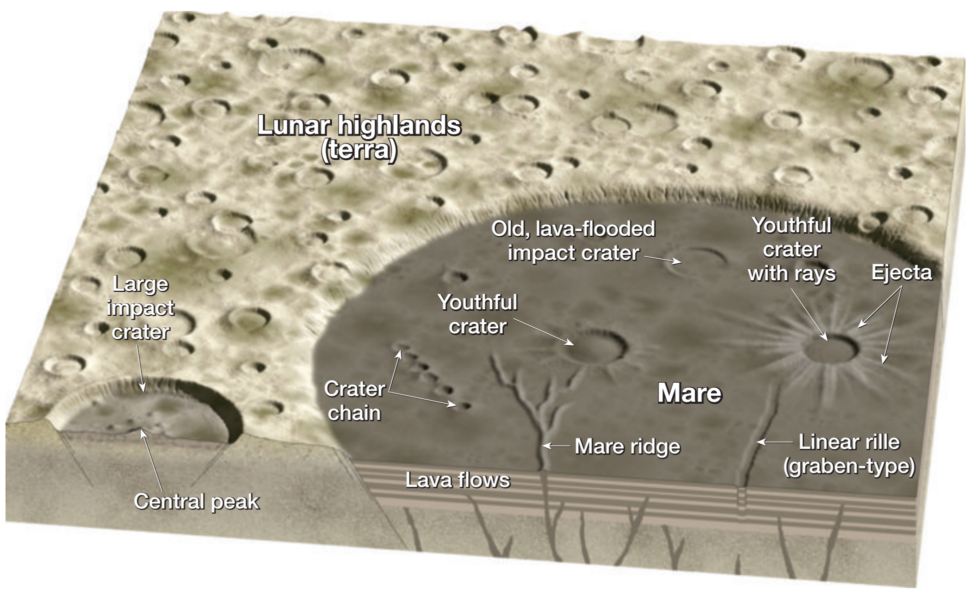


FIGURE 24.6 Block diagram illustrating major topographic features on the lunar surface.

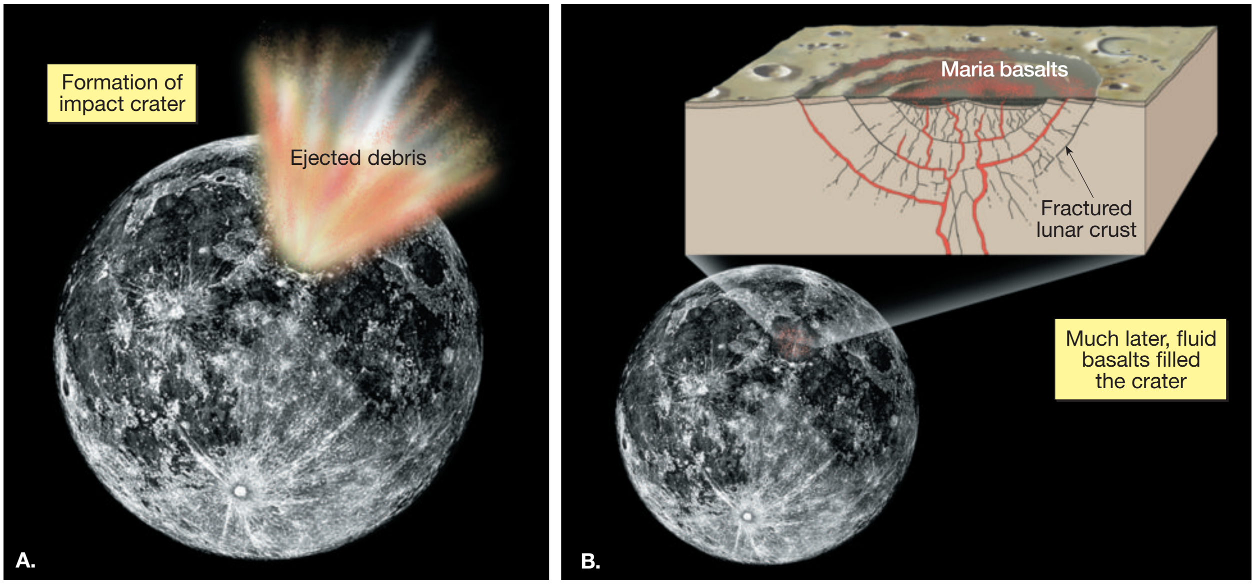


FIGURE 24.7 Formation of lunar maria. **A.** Impact of an asteroid-size mass produced a huge crater hundreds of kilometers in diameter and disturbed the lunar crust far beyond the crater. **B.** Filling of the impact area with fluid basalts, perhaps derived from partial melting deep within the lunar mantle.

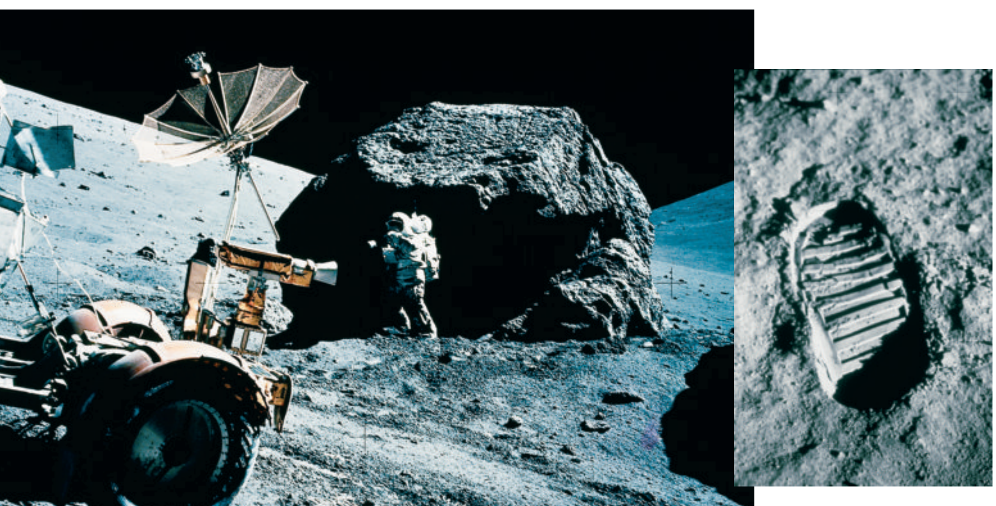
During the late stages of its accretion, the Moon's upper mantle was partially or completely melted, resulting in a magma ocean. Then about 4.4 billion years ago, the magma ocean began to cool and underwent magmatic differentiation (see Chapter 4). Most of the dense minerals, olivine and pyroxene, sank while the less dense plagioclase feldspar floated to form the Moon's crust. Once formed, the lunar crust was continually impacted as it swept up debris from the solar nebula. Then about 3.9 billion years ago the Moon, and probably the entire solar system, experienced a sudden drop in the rate of meteoritic bombardment. (Since that time, the rate of cratering has been roughly constant.) Remnants of this original crust are represented by the densely cratered highlands, which have been estimated to be as much as 4.4 billion years old.

The next major event was the formation of the large maria basins (see Figure 24.7). Radiometric dating of the maria basalts puts their age between 3.2 billion and 3.8 billion years, considerably younger than the initial lunar crust. In places, the lava flows overlap the highlands, another testimonial to the younger age of the maria deposits. Evidence suggests that some mare-forming eruptions may have occurred as recently as a billion years ago. However, no volcanism occurs today, perhaps because cooling caused the Moon's crust to become too thick for magma to penetrate.

The last prominent features to form on the lunar surface were the rayed craters, as exemplified by the 90 kilometer-wide Copernicus crater shown in Figure 24.3. Material ejected from these younger depressions is clearly seen blanketing the surfaces of the maria and many older rayless craters. Even a relatively young crater like Copernicus is thought to be about a billion years old. Had it formed on Earth, erosional forces would have long since obliterated it.

If photos of the Moon taken several hundreds of millions of years ago were available, they would reveal that the Moon has changed little in the intervening years. By all measures, the Moon is essentially a geologically dead body wandering through space and time.

FIGURE 24.8 Astronaut Harrison Schmitt sampling the lunar surface. Notice the footprints (inset) in the lunar "soil." (Courtesy of NASA)



The Planets: A Brief Tour

Mercury: The Innermost Planet

Mercury, the innermost and smallest planet, is hardly larger than Earth's Moon and is smaller than three other moons in the solar system. Mercury revolves quickly but rotates slowly. One full day–night cycle on Earth takes 24 hours, but on Mercury it requires 179 Earth-days. Thus, a night on Mercury lasts for about

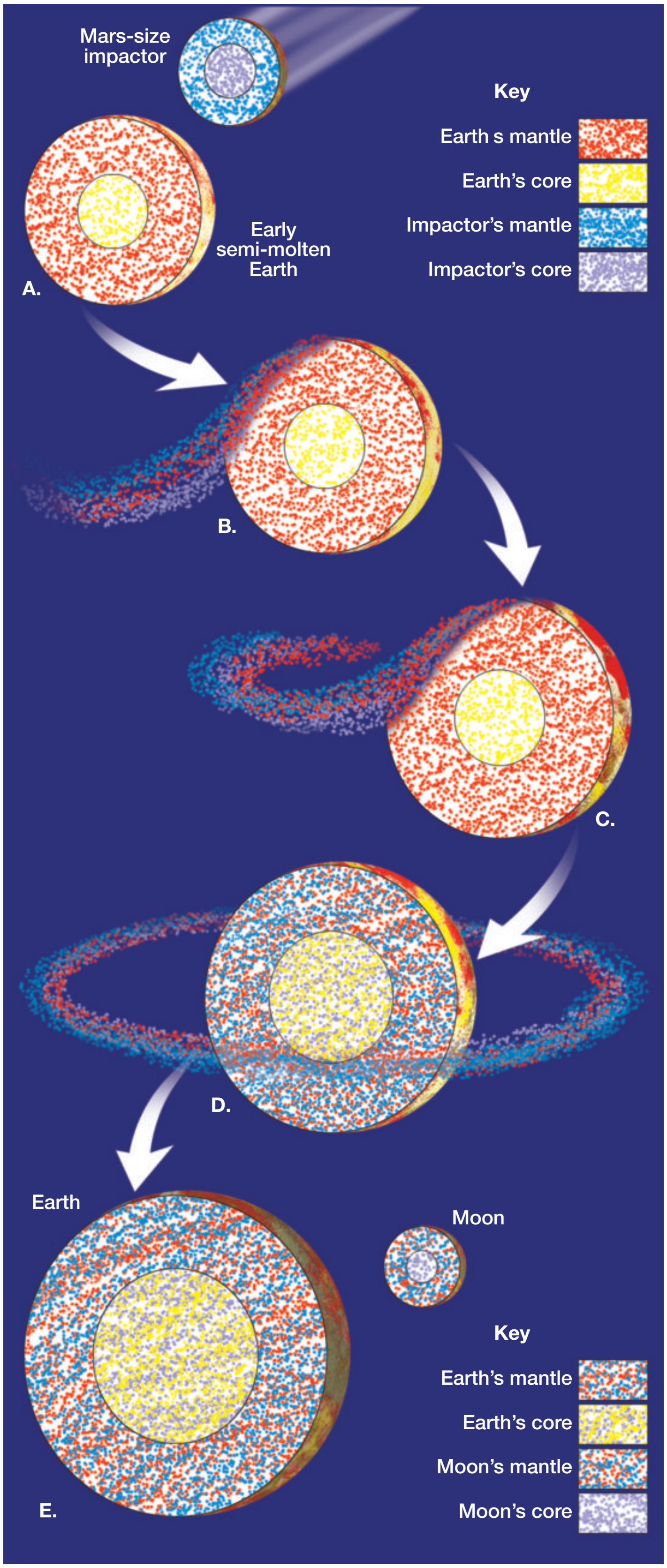


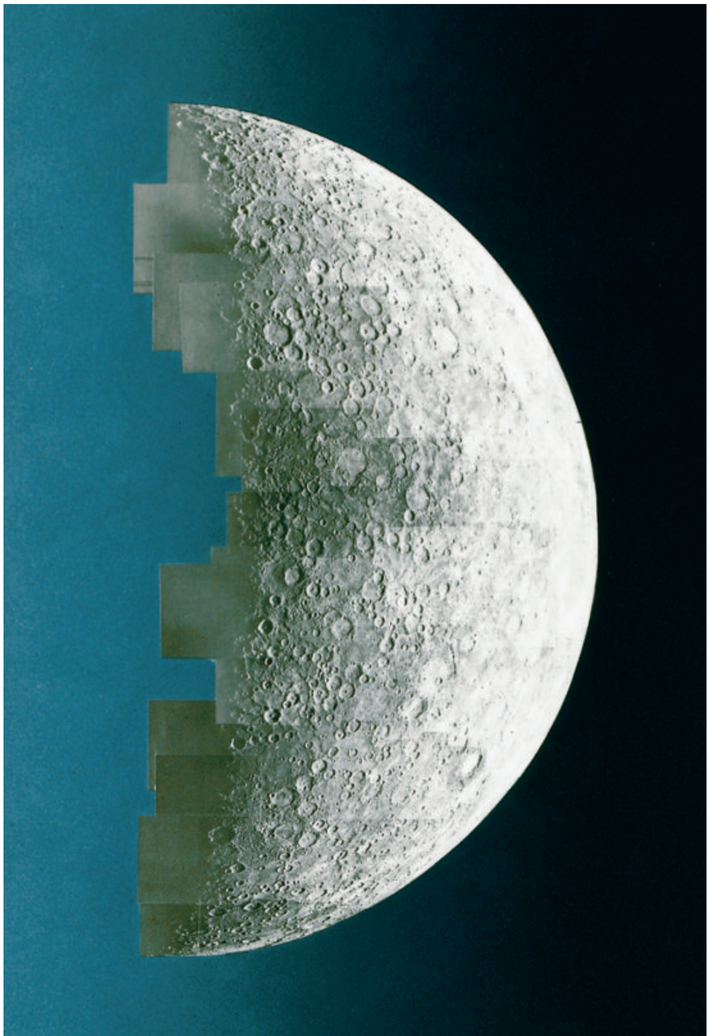
FIGURE 24.9 The formation of the Moon based on a scenario often called the impact theory. According to this model a protoplanet the size of Mars was involved in a glancing collision with a young semi-molten Earth. Most of the pieces of the protoplanet and splattered fragments of Earth coalesced in an orbit to form the Moon. Note that much of the impactor's core became part of Earth, leaving the Moon with a large rocky mantle and a comparatively small metallic core.

three months and is followed by three months of daylight. Nighttime temperatures drop as low as −173°C (−280°F) and noontime temperatures exceed 427°C (800°F), hot enough to melt tin and lead. Mercury has the greatest temperature extremes of any planet. The odds of life as we know it existing on Mercury are nil.

Like our own Moon, Mercury absorbs most of the sunlight that strikes it, reflecting only 6 percent into space (Figure 24.10). In contrast, the Earth reflects about 30 percent of the light that strikes it, much of it from clouds. The low reflectivity of sunlight from Mercury is characteristic of terrestrial bodies that have virtually no atmosphere. The minuscule amounts of gas present on Mercury may have originated as ionized gas emitted from the Sun; from the ices of a recent comet impact; from surface rocks subject to solar winds; and/or from outgassing of the planet's interior.

The probe *Messenger,* scheduled to arrive in 2011, will investigate the composition of Mercury's core and the nature of its magnetic field. Mercury is very dense ($5.4\ g/cm^3$), which implies that it contains a very large iron core for its size. Mercury has cratered highlands, much like the Moon, and vast smooth terrains that resemble maria. Mercury also has very long scarps that cut across the plains and numerous craters. These scarps are thought to be the result of

FIGURE 24.10 Photomosaic of Mercury. This view of Mercury is remarkably similar to the "far side" of Earth's Moon. (Courtesy of NASA)



Students Sometimes Ask . . .

Do any nearby stars have planets?

Yes. Although this was long suspected, it was not until recently that the presence of extrasolar planets was verified. Astronomers have identified these bodies by measuring the telltale wobbles of nearby stars. The first apparent planet outside the solar system was discovered in 1995, orbiting the star 51 Pegasi, 42 light-years from Earth. Since that time, over two dozen Jupiter-size bodies have been identified, most of them surprisingly close to the stars they orbit.

crustal shortening as the planet cooled and shrank early in its history. The shrinking caused the crust to fracture.

Venus: The Veiled Planet

Venus, second only to the Moon in brilliance in the night sky, is named for the goddess of love and beauty. It orbits the Sun in a nearly perfect circle once every 255 Earth-days. Venus is similar to Earth in size, density, mass, and location in the solar system. Thus, it has been referred to as "Earth's twin." Because of these similarities, it is hoped that a detailed study of Venus will provide geologists with a better understanding of Earth's evolutionary history.

FIGURE 24.11 This global view of the surface of Venus is computer-generated from two years of *Magellan* project radar mapping. The twisting bright features that cross the globe are highly fractured mountains and canyons of the eastern Aphrodite highland. (Courtesy of NASA/JPL)

Venus is shrouded in thick clouds impenetrable to visible light. The Venusian atmosphere contains an opaque cloud layer about 25 kilometers (15 miles) thick, and has an atmospheric pressure that is 90 times that at Earth's surface. Before the advent of space vehicles, Venus was considered to be a potentially hospitable site for living organisms. However, evidence from space probes indicates otherwise. The surface of Venus reaches temperatures as great as 475°C (900°F), and the Venusian atmosphere is 97 percent carbon dioxide. Only scant water vapor and nitrogen have been detected. This hostile environment makes it unlikely that life as we know it exists on Venus.

The composition of the Venusian core is likened to that of Earth. However, since Venus only has a small induced magnetic field, the internal dynamics must be very different. Mantle convection still operates on Venus, but the processes of plate tectonics, which recycle rigid lithosphere, do not appear to have contributed to the present Venusian topography. Tectonic activity on Venus seems to be restricted to upwelling (mantle plumes) and downwelling of material in the planet's interior, rather than lateral movement and subduction of lithospheric plates.

Radar mapping by the unmanned *Magellan* spacecraft and by instruments on Earth has revealed a varied topography with features somewhat between those of Earth and Mars (Figure 24.11). Radar pulses in the microwave range are sent toward the Venusian surface, and the heights of plateaus and mountains are measured by timing the return of the radar echo. These data have confirmed that basaltic volcanism and tectonic deformation are the dominant processes operating on Venus. Further, based on the low density of impact craters, volcanism and tectonic deformation must have been very active during the recent geologic past.

About 80 percent of the Venusian surface consists of subdued plains that are covered by volcanic flows. Some lava channels extend hundreds of kilometers; one meanders 6800 kilometers across the planet. Thousands of volcanic structures have been identified, mostly small shield volcanoes, although more than 1500 volcanoes greater than 20 kilometers (12 miles) across have been mapped (Figure 24.12). One is Sapas Mons, 400 kilometers (250 miles) across and 1.5 kilometers (0.9 mile) high. Many flows from this volcano erupted from its flanks rather than the summit, in the manner of Hawaiian shield volcanoes. Only 8 percent of the Venusian surface consists of highlands that may be likened to continental areas on Earth.

Mars: The Red Planet

Mars has evoked greater interest than any other planet, both for scientists and for nonscientists (see Box 24.1). When one imagines intelligent life on other worlds, little green Martians may come to mind. Interest in Mars stems mainly from this planet's accessibility to observation. All other planets within telescopic range have their surfaces hidden by clouds, except for Mercury, whose nearness to the Sun makes viewing difficult. Mars is approximately half the size

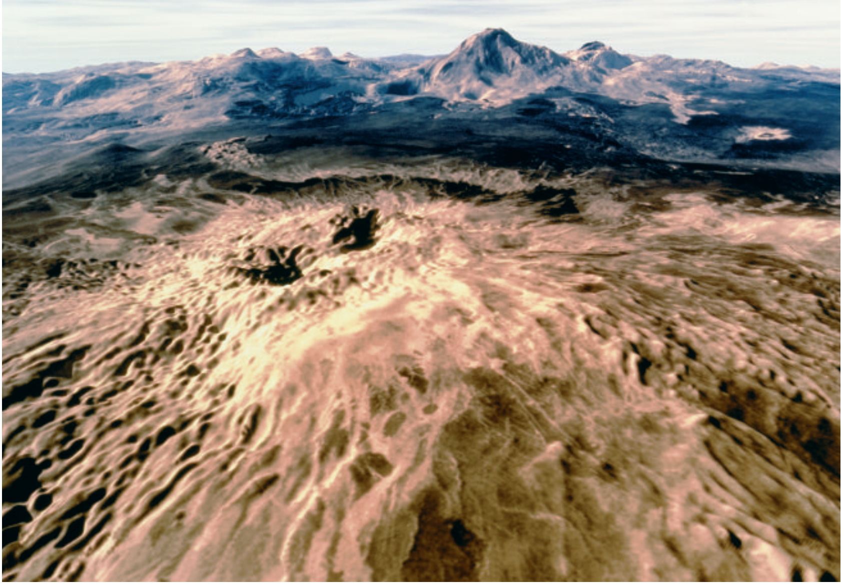


FIGURE 24.12 Computer-generated image of Venus. Near the horizon is Maat Mons, a large volcano. The bright feature below is the summit of Sapas Mons. (Courtesy David P. Anderson/SMU/NASA/Science Photo Library/Photo Researchers, Inc.)

of the Earth and revolves around the Sun in 687 Earth-days. Through the telescope, Mars appears as a reddish ball interrupted by some permanent dark regions that change intensity during the Martian year. The most prominent telescopic features of Mars are its brilliant white polar caps, resembling Earth's.

The Martian Atmosphere The Martian atmosphere has only 1 percent the density of Earth's, and it is primarily carbon dioxide with tiny amounts of water vapor. Data from Mars probes confirm that the polar caps of Mars are made of water ice, covered by a thin layer of frozen carbon dioxide. As winter nears in either hemisphere, we see the equatorward growth of that hemisphere's ice cap as temperatures drop to −125°C (−193°F) and additional carbon dioxide is deposited.

Although the atmosphere of Mars is very thin, extensive dust storms occur and may cause the color changes observed from Earth-based telescopes. Hurricane-force winds up to 270 kilometers (170 miles) per hour can persist for weeks. Images from *Viking 1* and *Viking 2* revealed a Martian landscape remarkably similar to a rocky desert on Earth (see chapter-opening photo), with abundant dunes and impact craters partially filled with dust.

Mars' History Although the Martian core is believed to be solid because of the lack of a global magnetic field, evidence suggests that some of the planet's oldest rocks formed in the presence of a strong magnetic field. In the past, Mars may have had a hot interior with a molten core.

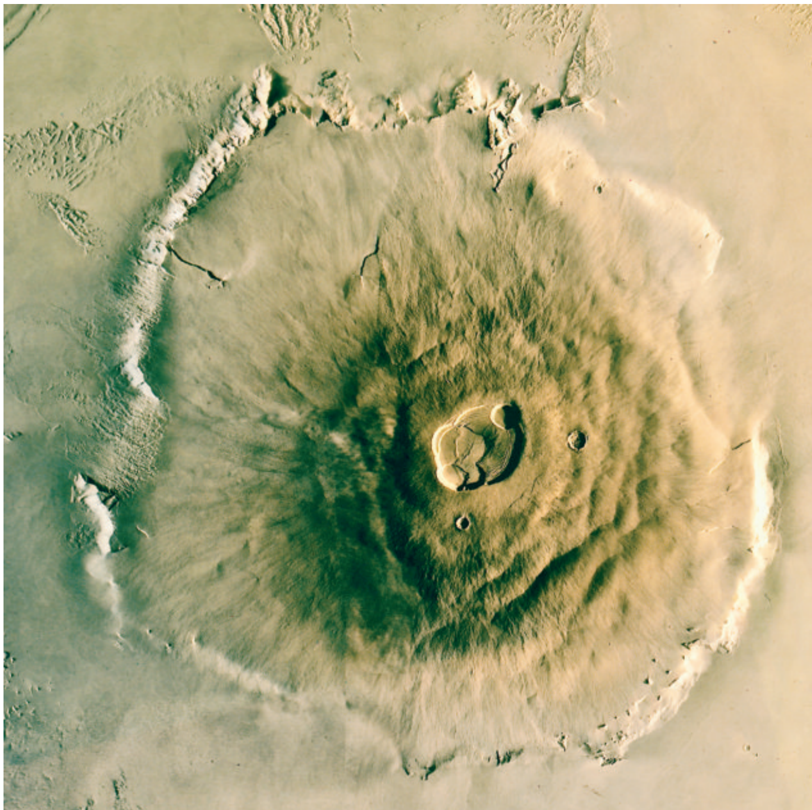
Most Martian surface features are old by Earth standards. Evidence suggests that weathering accounts for almost all surface changes during the last 3.5 billion years. Denser cratering in the highlands indicates that these areas are very old, whereas lighter cratering in the lowlands suggest volcanic eruptions 3.7–3.8 billion years ago. The highly cratered southern hemisphere is probably similar in age to the lunar highlands (nearly 4.5 billion years old). Even the relatively fresh-appearing volcanic features of the northern hemisphere are most likely older than several hundred million years. These facts and the absence of Marsquake recordings by *Viking* seismographs point to a tectonically dead planet.

Mars' Dramatic Geological Past *Mariner 9*, the first spacecraft to orbit another planet, reached Mars in 1971 amid a raging dust storm. When the dust cleared, images of Mars' northern hemisphere revealed numerous large volcanoes. The biggest, Olympus Mons, is the size of Ohio and 23 kilometers (75,000 feet) tall, nearly three times higher than Mount Everest. This gigantic volcano was last active about 100 million years ago and resembles Hawaiian shield volcanoes on Earth (Figure 24.13).

Why are the volcanoes on Mars many times larger than even the biggest volcanic structures on Earth? The largest volcanoes on terrestrial planets tend to form where plumes of hot rock rise from deep within its interior. Earth is tectonically active, with moving plates that keep the crust in constant motion. The Hawaiian Islands, for example, consist of a chain of shield volcanoes that formed as the Pacific plate moved over a relatively stationary mantle plume. On Mars, volcanoes such as Olympus Mons have grown to great size because the crust there remains stationary. Successive eruptions occur from a mantle plume at the same location and add to the bulk of a single volcano rather than producing several smaller structures, as occurs on Earth.

Another surprising find made by *Mariner 9* was the existence of several canyons that dwarf even Earth's Grand Canyon of the Colorado River. One of the largest, Valles

FIGURE 24.13 Image of Olympus Mons, an inactive shield volcano on Mars that covers an area about the size of the state of Ohio. (Courtesy of the U.S. Geological Survey)



BOX 24.1 ▶ UNDERSTANDING EARTH

Pathfinder—The First Geologist on Mars

On July 4, 1997, the *Mars Pathfinder* bounced onto the rock-littered surface of Mars and deployed its wheeled companion, *Sojourner.* Over the next three months the lander sent three gigabits of data back to Earth, including 16,000 images and 20 chemical analyses. The landing site was a vast rolling landscape carved by ancient floods. The flood-deposit locale was selected with hope that a variety of rock types would be available for the rover *Sojourner* to examine.

Sojourner carried an alpha photon X-ray spectrometer (APXS) used to determine the chemical composition of rocks and Martian "soil" (regolith) at the landing site (Figure 24.A). In addition, the rover was able to take close-up images of the rocks. From these images, researchers concluded that the rocks were igneous. However, one hard, white, flat object named Scooby Doo was originally thought to be a sedimentary rock, but the APXS data suggest its chemistry is like that of the soil found at the site. Thus, Scooby Doo is probably a well-cemented soil.

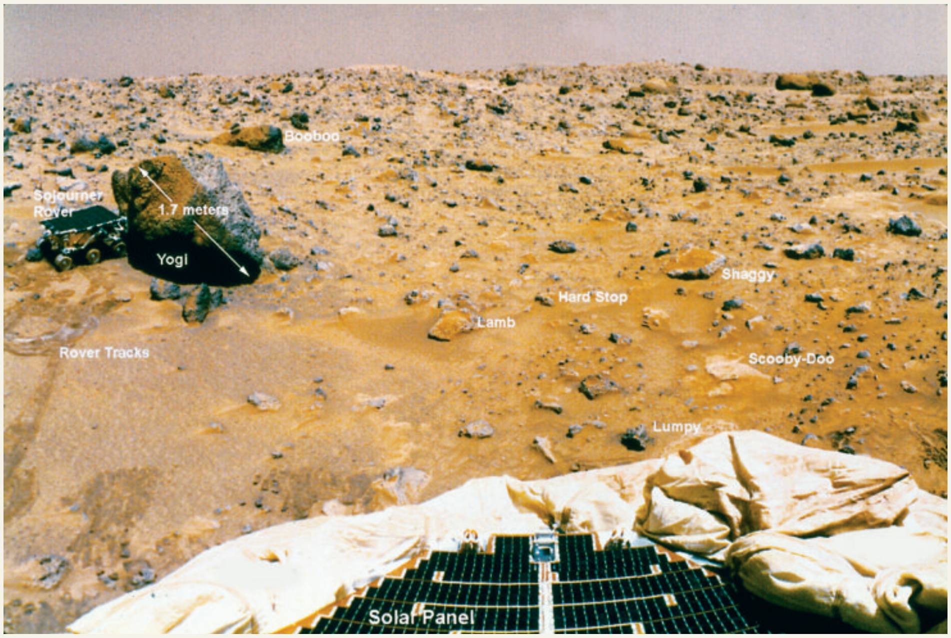


FIGURE 24.A *Pathfinder*'s rover *Sojourner* (left) obtaining data on the chemical composition of a Martian rock known as Yogi. (Photo courtesy of NASA)

During its first week on Mars, *Sojourner's* APXS obtained data for a patch of windblown soil and a medium-sized rock, known affectionately as Barnacle Bill. Preliminary evaluation of the APXS data from Barnacle Bill showed that it contained over 60 percent silica. This could indicate that the volcanic rock andesite is present on Mars. However, researchers had expected that most volcanic rocks on Mars would be basalt, which is lower in silica (less than 50 percent). On Earth, andesites are associated with tectonically active regions where oceanic crust is subducted into the mantle. Examples include the volcanoes of South America's Andes Mountains and the Cascades of North America. It is not clear whether the rocks are andesite or basalt with an andesite coating caused by weathering of the basalt.

In all, *Sojourner* analyzed eight rocks and seven soils, and the results are controversial. Because these rocks are covered with a reddish dust that is high in sulfur, the exact composition of the rocks is debated. Some researchers claim they are all of the same composition, and that the differences between the measurements are due to varying thicknesses of dust.

Marineris, is thought to have formed by slippage of material along huge faults in the outer crustal layer. In this respect, it would be comparable to the rift valleys of East Africa (Figure 24.14).

Water on Mars? Liquid water does not appear to exist anywhere on the Martian surface. However, poleward of about 30 degrees latitude ice can be found within a meter of the surface and in the polar regions it forms small permanent ice caps. In addition, considerable evidence indicates that in the first billion years of the planet's history, liquid water flowed on the surface creating valleys and related features. In particular, some areas of Mars exhibit treelike drainage patterns similar to those created by streams on Earth. When these streamlike channels were first discovered, some observers speculated that a thick, water-rich atmosphere capable of generating torrential downpours once existed on Mars. Other researchers, however, were skeptical.

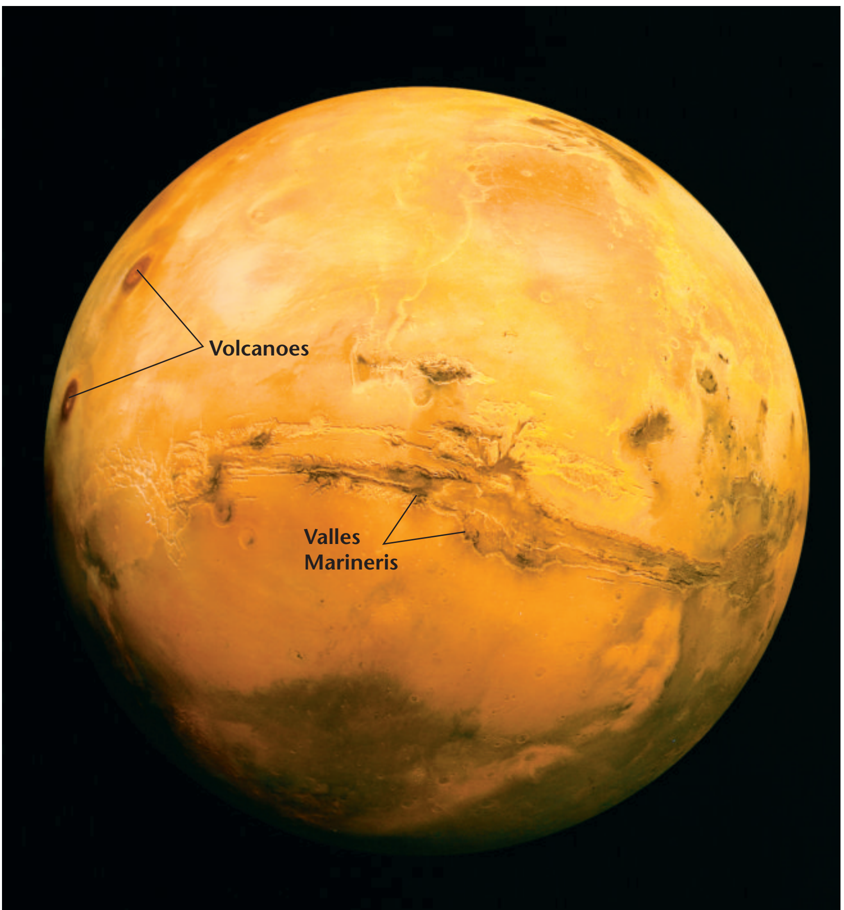
Today, most planetary geologists agree that running water was involved in carving at least some of the valleys on Mars. Some examples can be seen on an image from the *Mars Global Surveyor* in Figure 24.15A. Researchers have proposed that melting of subsurface ice caused springlike seeps to emerge along this valley wall, slowly creating the gullies shown.

Other channels have streamlike banks and contain numerous teardrop-shaped islands (24.15B). These valleys appear to have been cut by catastrophic floods that had discharge rates that were more than 1000 times greater than the Missippippi 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 valleys is the melting of subsurface ice. If the meltwater was trapped beneath a thick layer of permafrost, pressure could mount until a catastrophic release of groundwater occurred. As a result, the overlying surface layer would collapse, creating the chaotic terrain.

Not all Martian valleys appear to be the result of water released by the melting of subsurface ice. Some that exhibit branching treelike patterns that closely resemble the drainage networks on Earth were likely part of an active hydrologic cycle.

Recent evidence for surface water comes from the *Spirit* and *Opportunity* rovers. *Opportunity* investigated geologic structures similar to formations created by water on Earth—layered sedimentary rock, playas, and lake beds. Minerals that form only in the presence of water such as hydrated sulfates and micas were detected. Small spheres of hematite, called "blueberries," were also found that probably precipitated from water to form lake sediments. Although these findings are new, water does not appear to have significantly altered the topography of Mars for billions of years with the exception of the polar regions. Near the poles, the *Mars Express Orbiter* and *Mars Odyssey* detected geologically recent glacial and snow deposits. Polygonal patterned ground similar to features associated with permafrost are also commonly seen on Mars (Figure 24.16).

FIGURE 24.14 This image shows the entire Valles Marineris canyon system, over 5000 kilometers long and up to 8 kilometers deep. The dark spots on the left edge of the image are huge volcanoes, each about 25 kilometers high. (Courtesy of U.S. Geological Survey)



The Martian Satellites Tiny Phobos and Deimos, the two satellites of Mars, were not discovered until 1877 because they are only 24 and 15 kilometers, in diameter. Phobos is nearer to its parent than any other natural satellite in the solar system—only 5500 kilometers (3400 miles)—and requires just 7 hours and 39 minutes for one revolution. *Mariner 9* revealed that both satellites are irregularly shaped and have numerous impact craters.

It is likely that these moons are asteroids captured by Mars. A most interesting coincidence in astronomy and literature is the close resemblance of Phobos and Deimos to two fictional satellites of Mars described by Jonathan Swift in *Gulliver's Travels*, written about 150 years before these satellites were actually discovered.

Jupiter: Lord of the Heavens

Jupiter, truly a giant among planets, has a mass two and a half times greater than the combined mass of all the remaining planets, satellites, and asteroids. In fact, had Jupiter been about 10 times larger, it would have evolved into a small star. Despite its great size, however, it is only 1/800 as massive as the Sun.

Jupiter revolves around the Sun once every 12 Earth-years, and rotates more rapidly than any other planet, completing one rotation in slightly less than 10 hours. The effect of this fast spin is to make the equatorial region bulge and to make the polar dimension contract (see the Polar Flattening column in Table 24.1).

Atmosphere, Structure, and Composition When viewed through a telescope or binoculars, Jupiter appears to be covered with alternating bands of multicolored clouds aligned parallel to its equator (Figure 24.17). The most striking feature is the *Great Red Spot* in the southern hemisphere (Figure 24.17). The Great Red Spot has been a prominent feature since it was first seen more than three centuries ago. When *Voyager 2* swept by Jupiter in 1979, the Great Red Spot was the size of two Earth-size circles placed side by side. On occasion, it has grown even larger. Images from *Pioneer 11* as it moved near Jupiter's cloud tops in 1974 indicated that the Great Red Spot is a counterclockwise-rotating storm caught between two jetstream-like bands flowing in opposite directions. This huge, hurricane-like storm makes a complete rotation about once every 12 days.

As on other planets, the winds on Jupiter are the product of differential heating, which generates vertical convective motions in the atmosphere. Jupiter's convective flow produces alternating dark-colored *bands* and light-colored *zones* as shown in Figure 24.18. The light clouds (zones) are regions where warm material is ascending and cooling, whereas cool material is sinking in the dark belts. This convective circulation, along with Jupiter's rapid rotation, generates the high-speed, east–west flow observed between the

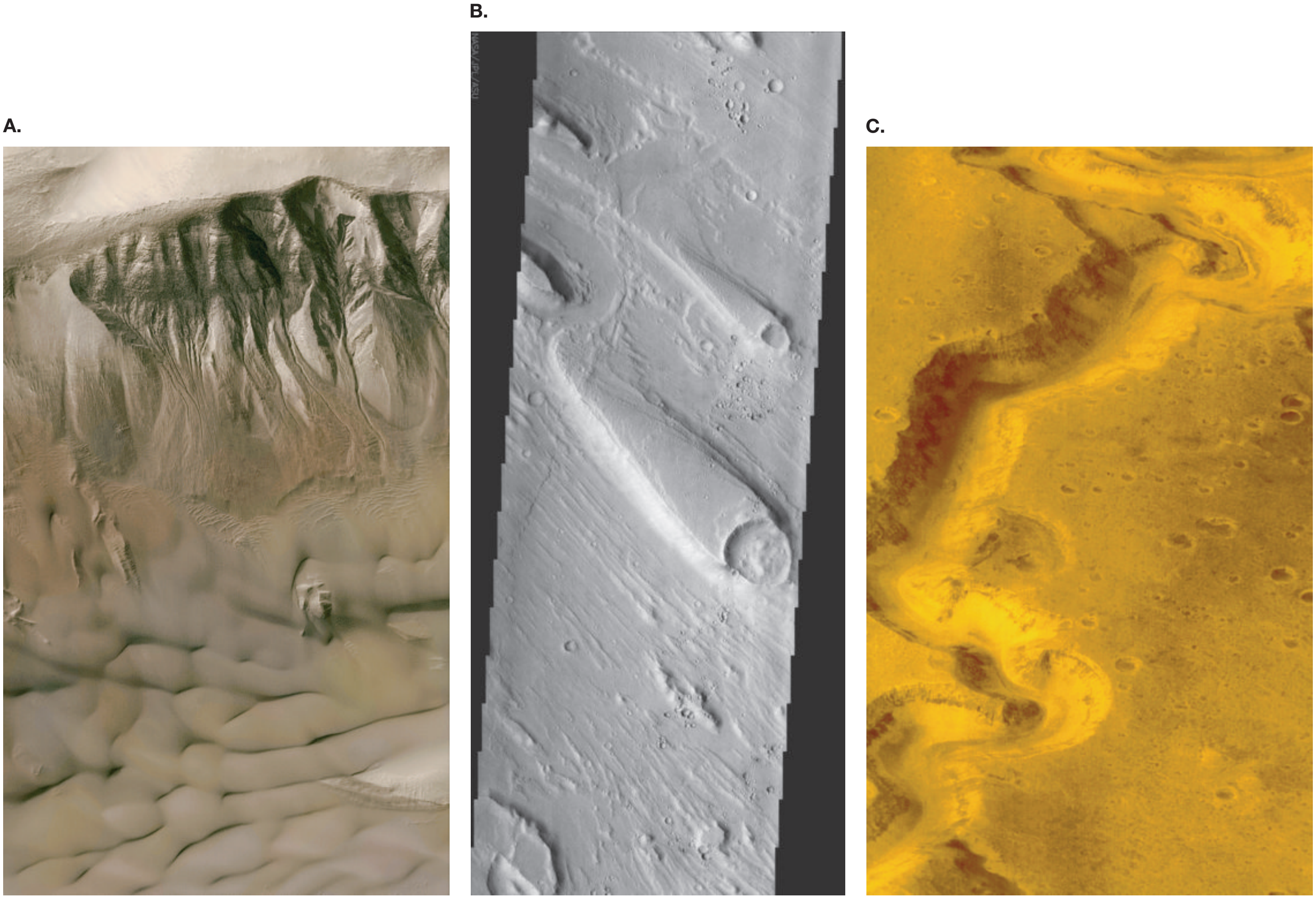


FIGURE 24.15 Evidence for erosion by running water. **A.** Image from *Mars Global Surveyor* showing crater wall with large gullies that may have been cut by liquid water, mixed with soil, rocks, and ice. (NASA/JPL photo courtesy of National Geographic) **B.** Streamlined islands in Ares Valles formed where running water encountered obstacles along its path. (NASA image) **C.** Terraces and a small central channel suggest that Nanedi Vallis may have been carved by running water. (NASA image)

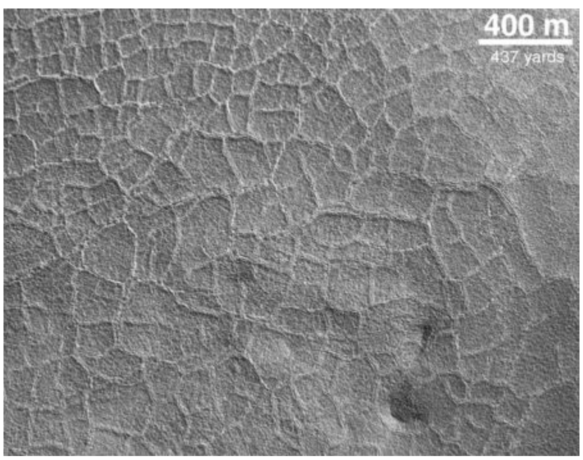


FIGURE 24.16 Polygonal patterned ground, shown here on Mars, is common in areas of permafrost in polar latitudes on Earth. (Courtesy of JPL/NASA)

belts and zones. Unlike winds on Earth, which are driven by solar energy, Jupiter gives off nearly twice as much heat as it receives from the Sun. Thus, it is the heat emanating from Jupiter's interior that produces the huge convection currents observed in its atmosphere.

Jupiter's atmosphere is composed mainly of hydrogen and helium but also contains lesser amounts of methane, ammonia, and water which form clouds composed of liquid droplets or ice crystals. Atmospheric pressure at the top of the clouds is equal to sea-level pressure on Earth. Because of Jupiter's immense gravity, the pressure increases rapidly toward its surface. At 1000 kilometers below the clouds, the pressure is great enough to compress hydrogen gas into a liquid. Consequently, Jupiter's surface is thought to be a gigantic ocean of liquid hydrogen. Less than halfway into Jupiter's interior, extreme pressures cause the liquid hydrogen to turn into *liquid metallic* hydrogen. The fast rotation and liquid metallic core are a possible explanation for the

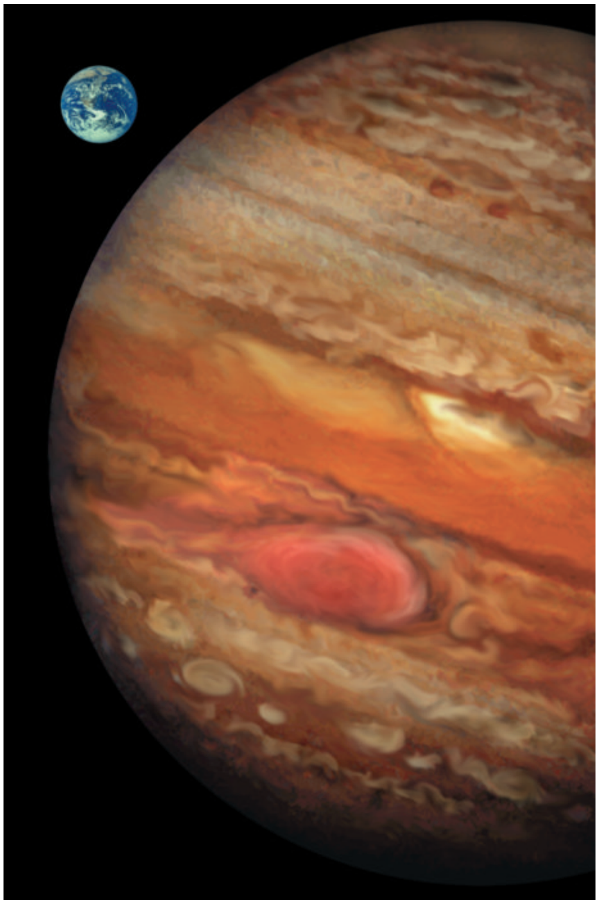


FIGURE 24.17 Artist's view of Jupiter with Great Red Spot visible in its southern hemisphere. Earth for scale.

intense magnetic field surrounding Jupiter. Jupiter is also believed to contain as much rocky and metallic material as is found in the terrestrial planets, probably located in a central core.

Jupiter's Moons Jupiter's satellite system, consisting of 63 moons discovered so far, resembles a miniature solar system. The four largest satellites, discovered by Galileo, travel in nearly circular orbits around the planet, with periods of from 2 to 17 Earth-days (Figure 24.19). The two largest Galilean satellites, Callisto and Ganymede, surpass Mercury in size, whereas the two smaller ones, Europa and Io, are about the size of Earth's Moon. 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 almost everyone, that each of the four Galilean satellites is a unique geological world (Figure 24.19). A further surprise from the *Galileo* mission was that the composition of each satellite is strikingly different, which implies a different evolution for each satellite. For example, Ganaymede's has a dynamic core that generates a strong magnetic field not observed on the other satellites.

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 the surface of Io to heights approaching 200 kilometers (120 miles) (Figure 24.20A). The heat source for volcanic activity is tidal energy generated by a relentless "tug of war" between Io and Jupiter and the other Galilean satellites. The gravitational field of Jupiter and the other nearby satellites pulls and pushes on Io's tidal bulge as its slightly eccentric orbit takes it alternately closer to and farther from its parent planet. This gravitational flexing of Io is transformed into heat energy (similar to the back-and-forth bending of a paper clip) and results in Io's spectacular sulfurous volcanic eruptions. Moreover, lava thought to be mostly composed of silicate minerals regularly erupts on its surface (Figure 24.20B).

In addition, Jupiter has numerous satellites that are very small (about 20 kilometers in diameter), revolve in a direction that is opposite (*retrograde motion*) of the largest moons, and have orbits that are steeply inclined to the Jovian equator. These satellites appear to be asteroids that passed near enough to be captured gravitationally by Jupiter.

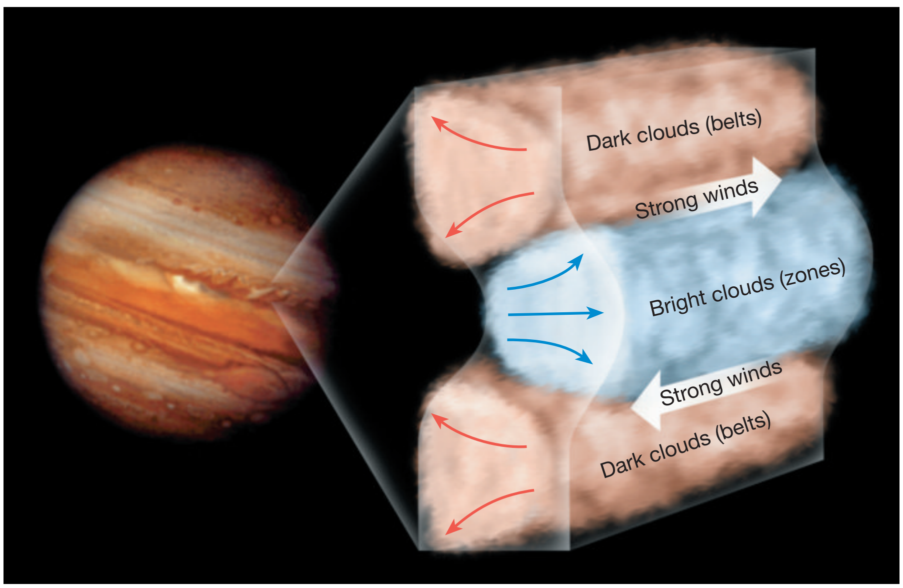


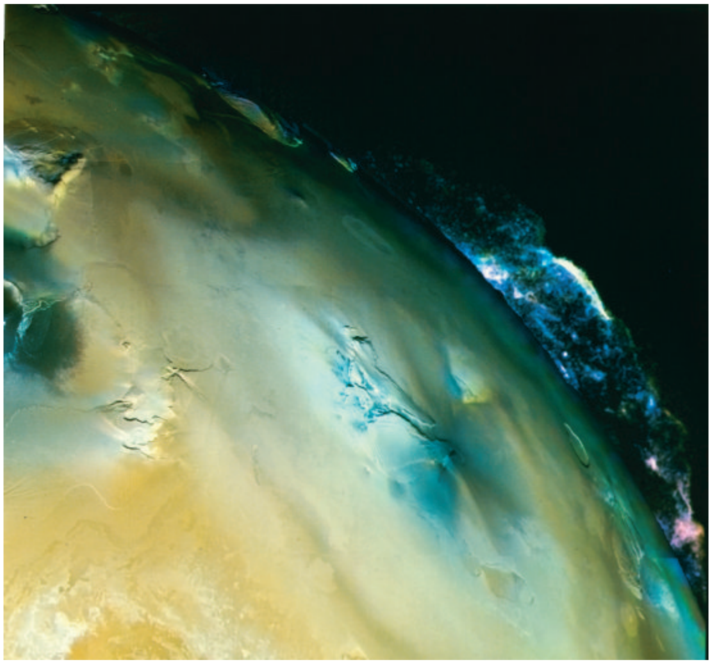
FIGURE 24.18 The structure of Jupiter's atmosphere. The areas of light clouds (zones) are regions where gases are ascending and cooling. Sinking dominates the flow in the darker cloud layers (belts). This convective circulation, along with the rapid rotation of the planet, generates the high-speed winds observed between the belts and zones.

Jupiter's Rings One of the interesting aspects of the *Voyager 1* mission was a study of Jupiter's ring system. By analyzing how these rings scatter light, researchers determined that the rings are composed of fine, dark particles, similar in size to smoke particles. Further, the faint nature of the rings indicates that these minute particles are

A. Io B. Europa C. Ganymede D. Callisto

FIGURE 24.19 Jupiter's four largest moons (from left to right) are called the Galilean moons because they were discovered by Galileo. **A.** The innermost moon, Io, is one of only three volcanically active bodies in the solar system. **B.** Europa, smallest of the Galilean moons, has an icy surface that is criss-crossed by many linear features. **C.** Ganymede, the largest Jovian satellite, contains cratered areas, smooth regions, and areas covered by numerous parallel grooves. **D.** Callisto, the outermost of the Galilean satellites, is densely cratered, much like Earth's moon. (Courtesy of NASA/NGS Image Collection)

A.



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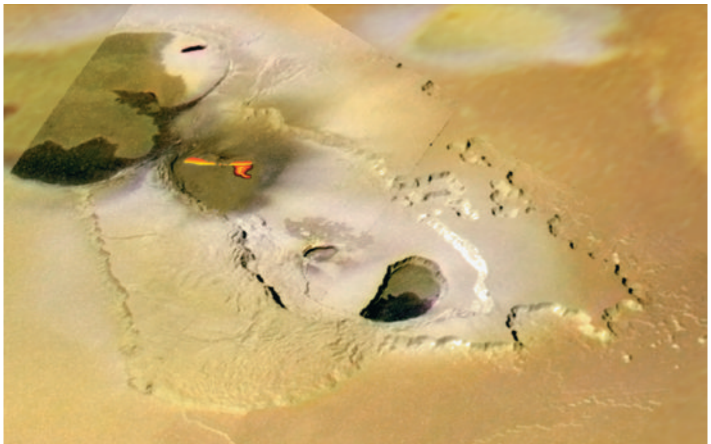


Students Sometimes Ask . . .

Besides Earth, do any other bodies in the solar system have liquid water?

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 to have water in the liquid form (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, Europa is suspected to have an ocean of liquid water hidden under its outer covering of ice. Detailed images sent back from the *Galileo* spacecraft 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—and perhaps an ocean. Because the presence of water in the liquid form is a necessity for life as we know it, there has been much interest in sending an orbiter to Europa—and eventually a lander capable of launching a robotic submarine—to determine if it may harbor life.

FIGURE 24.20 A volcanic eruption on Jupiter's Moon Io. **A.** This plume of volcanic gases and debris is rising over 100 kilometers (60 miles) above Io's surface. **B.** The bright area on the left side of the image is newly erupted hot lava. (Courtesy of NASA) widely dispersed. The main ring is composed of particles believed to be fragments blasted by meteorite impacts from the surfaces of Metis and Adrastea, two small moons of Jupiter. Impacts on Jupiter's moon's Amalthea and Thebe are believed to be the sources of the outer Gossamer ring.

Saturn: The Elegant Planet

Requiring 29.46 Earth-years to make one revolution, Saturn is almost twice as far from the Sun as Jupiter, yet its atmosphere, composition, and internal structure are believed to be remarkably similar to Jupiter's. The most prominent feature of Saturn is its system of rings (Figure 24.21), first seen by Galileo in 1610. With his primitive telescope, the rings appeared as two small bodies adjacent to the planet. Their ring nature was determined 50 years later by the Dutch astronomer Christian Huygens.

Structure of Saturn Saturn's atmosphere is very dynamic, with winds roaring at up to 1500 kilometers (930 miles) per hour. Cyclonic "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 are composed of ammonia, ammonia hydrosulfide, and water, each segregated by temperature. The central core is composed of rock and ice layered with liquid metallic hydrogen, and then liquid hydrogen. Like Earth, Saturn's magnetic field is believed to be created within the core. In this process, helium condenses in the liquid hydrogen layers, releasing the heat necessary for convection.

In 1980 and 1981, the nuclear-powered *Voyagers* 1 and 2 space probes came within 100,000 kilometers of Saturn. More information was gained in a few days than had been acquired in all the time since Galileo first viewed this elegant planet telescopically. More recently, observations from ground-based telescopes and the *Hubble Space Telescope* 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, reducing the glare from the main rings, Saturn's faintest rings and satellites became visible.

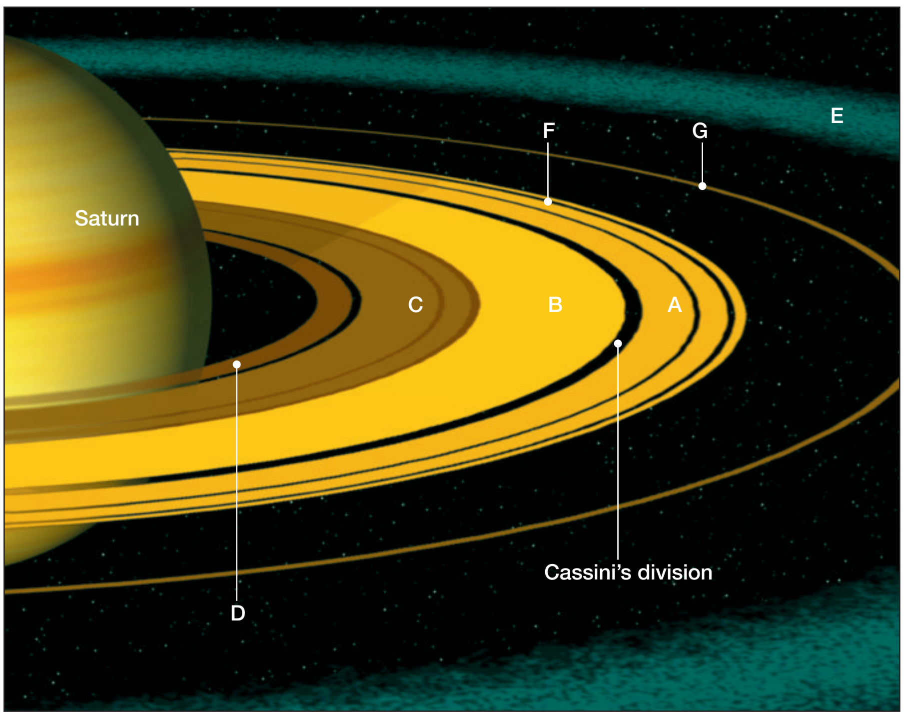


FIGURE 24.21 A view of Saturn's dramatic ring system.

Planetary Ring Systems Until the recent discovery that Jupiter, Uranus, and Neptune also have ring systems, this phenomenon was thought to be unique to Saturn. Although the four known ring systems differ in detail, they share many attributes. They all consist of multiple concentric rings separated by gaps of various widths. In addition, each ring is composed of individual particles—"moonlets" of ice and rock—that circle the planet while regularly impacting one another.

Most rings fall into one of two categories based on particle density. Saturn's main rings (designated A and B in Figure 24.21) and the bright rings of Uranus are tightly packed and contain "moonlets" that range in size from a few centimeters (pebble-size) to several meters (house-size). These particles are thought to collide frequently as they orbit the parent planet. Despite the fact that Saturn's dense rings stretch across several hundred kilometers, they are very thin, perhaps less than 100 meters (300 feet) from top to bottom.

At the other extreme, the faintest rings, such as Jupiter's ring system and Saturn's outermost ring (designated E in Figure 24.21), are composed of very fine (smoke-size) particles that are widely dispersed. In addition to having very low particle densities, these rings tend to be thicker than Saturn's bright rings.

Recent studies have shown that the moons that coexist with the rings play a major role in determining their structure. In particular, the gravitational influence of these moons tends to shepherd the ring particles by altering their orbits. The narrow rings appear to be the work of satellites located on either side that confine the ring by pulling back particles that try to escape.

More importantly, the ring particles are believed to be debris ejected from these moons, including the volcanic "ash" that spews from Jupiter's moon Io. Recent evidence from the *Cassini* mission shows the moon Enceladus has a hot spot with geysers spewing water ice that contributes to Saturn's E ring. It is possible that material is continually being recycled between the rings and the ring moons. The 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

FIGURE 24.22 Montage of the Saturnian satellite system. The moon Dione is in foreground; Tethys and Mimas are at lower right; Enceladus and Rhea are off ring's left; and Titan is upper right. (Photo courtesy of NASA)

that we once thought; rather, they continually reinvent themselves.

The origin of planetary ring systems is still being debated. Perhaps the rings formed out of a flattened cloud of dust and gases that encircled the parent planet. In this scenario, the rings formed at the same time and of the same material as the planets and moons. 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 blasted apart 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 four-year tour of Saturn.

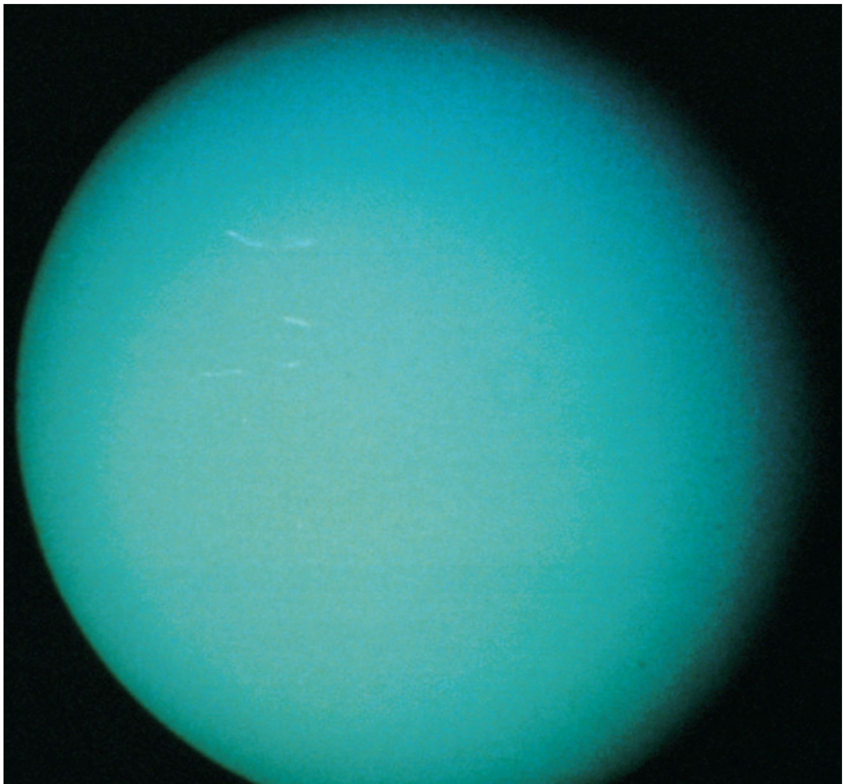
Saturn's Moons The Saturnian satellite system consists of 56 known moons (Figure 24.22). (If you count the "moonlets" that comprise Saturn's rings, this planet has millions of satellites.) The largest, Titan, is bigger than Mercury and is the second-largest satellite in the solar system (after Jupiter's Ganymede). Titan and Neptune's Triton are the only satellites in the solar system known to have a substantial atmosphere. Because of its dense gaseous cover, the atmospheric pressure at Titan's surface is about 1.5 times that at the Earth's surface. The Cassini-Huygens probe determined the atmospheric composition to be about 95 percent nitrogen and 5 percent methane with additional organic compounds—similar to Earth's primitive atmosphere prior to the onset of life. Recent evidence suggests that Titan has Earth-like geological landforms and geological processes, such as dune formation and fluvial erosion caused by methane rain. Another satellite, Phoebe, exhibits retrograde motion. It, like other moons with retrograde orbits, is most likely a captured asteroid or large planetesimal left over from the episode of planetary formation.

Uranus and Neptune: The Twins

While Earth and Venus have many similar traits, Uranus and Neptune are nearly twins, having similar structures and compositions. They are less than 1 percent different in diameter (about four times the size of Earth), and they are both bluish in appearance, which is attributable to the methane in their atmospheres (Figures 24.23 and 24.24). Uranus and Neptune take 84 and 165 Earth-years, respectively, to complete one revolution around the Sun. The core composition is similar to the other gas giants with a rocky silicate and iron core, but with less liquid metallic hydrogen and more ice than Jupiter and Saturn. Neptune, however, is colder, because it is half again as distant from the Sun as is Uranus.

Uranus: The Sideways Planet A unique feature of Uranus is that it rotates "on its side." Its axis of rotation, instead of being generally perpendicular to the plane of its orbit, like the other planets, lies nearly parallel to the plane of its orbit. Its rotational motion, therefore, has the appearance of a rolling ball, rather than the toplike spinning of other planets. This is likely due to a huge impact early in the planet's evolution that literally knocked Uranus on its side. Because the axis of Uranus is inclined more than 90 degrees, the Sun is nearly overhead at one of its poles once each revolution, and then half a revolution later it is overhead at the other pole.

FIGURE 24.23 This image of Uranus was sent back to Earth by *Voyager 2* as it passed by this planet on January 24, 1986. Taken from a distance of nearly 1 million kilometers, little detail of its atmosphere is visible, except a few streaks (clouds) in the northern hemisphere. (Courtesy of NASA)



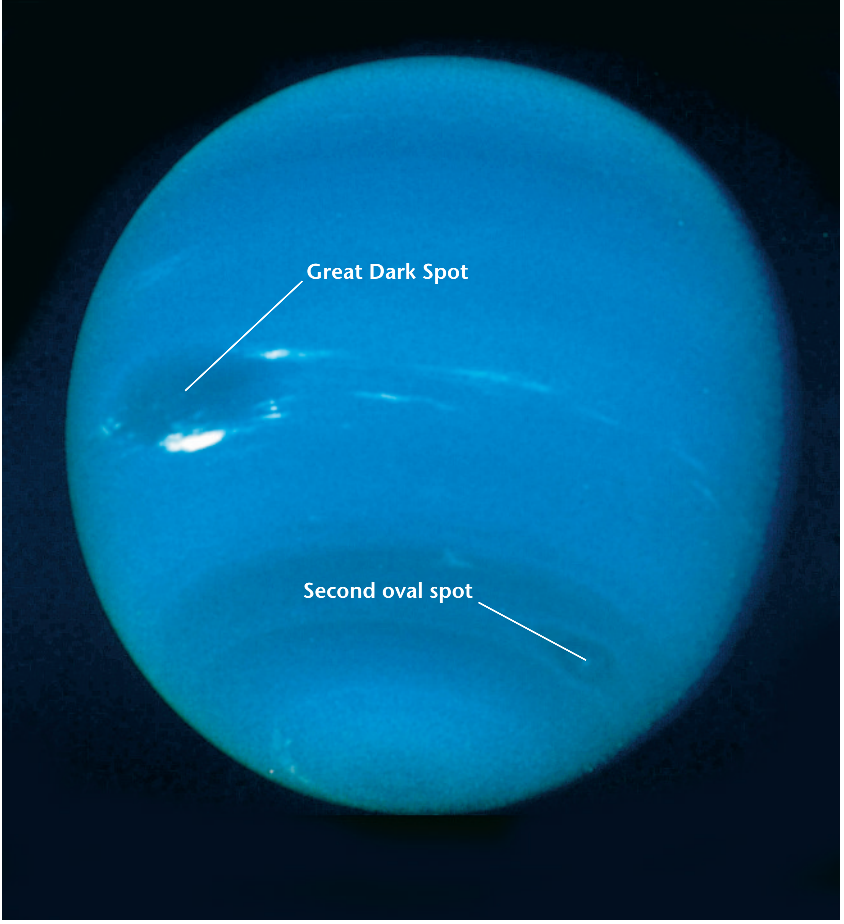


FIGURE 24.24 This image of Neptune shows the Great Dark Spot (left center). Also visible are bright cirruslike clouds that travel at high speed around the planet. A second oval spot is at south latitude on the east side of the planet. (Courtesy of the Jet Propulsion Laboratory)

A surprise discovery in 1977 revealed that Uranus has a ring system. This find occurred 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. Later studies indicate that Uranus has *at least* nine distinct belts of debris orbiting its equatorial region.

Spectacular views from *Voyager 2* of the five largest moons of Uranus show quite varied terrains. Some have long, deep canyons and linear scars, whereas others possess large, smooth areas on otherwise crater-riddled surfaces. The Jet Propulsion Laboratory described Miranda, the innermost of the five largest moons, as having a greater variety of landforms than any body yet examined in the solar system. These features indicate that Miranda was recently geologically active.

Neptune: The Windy Planet Even when the most powerful telescope is focused on Neptune, it appears a bluish fuzzy disk. Until the 1989 *Voyager 2* encounter, astronomers knew very little about this planet. However, the 12-year, nearly 3-billion-mile journey of *Voyager 2* provided investigators with so much new information about Neptune and its satellites that years will still be needed to analyze it all.

Neptune has a dynamic atmosphere, much like those of Jupiter and Saturn (Figure 24.24). Winds exceeding 1000 kilometers (600 miles) per hour encircle the planet, making it one of the windiest places in the solar system. It also has an Earth-size blemish called the *Great Dark Spot* that is reminiscent of Jupiter's Great Red Spot and is assumed to be a large rotating storm. About five years after the *Voyager 2* encounter, when the *Hubble Space Telescope* viewed Neptune, the spot had vanished, and was replaced by another dark spot in the planet's northern hemisphere.

Perhaps most surprising are white, cirruslike clouds that form a layer about 50 kilometers above the main cloud deck, probably frozen methane. Six new satellites were discovered in the *Voyager* images, bringing Neptune's family to 8, and more recent observations bring the total to 13. All of the newly discovered moons orbit the planet in a direction opposite that of the two larger satellites. *Voyager* images also revealed a ring system around Neptune.

Triton, Neptune's largest moon, is a most interesting object. It is the only large moon in the solar system that exhibits retrograde motion. This indicates that Triton formed independently of Neptune and was gravitationally captured.

Triton, along with other moons of the Jovian planets, exhibits one of the most amazing manifestations of volcanism, the eruption of ices. This type of volcanism is termed **cryovolcanism** (from the Greek *Kryos*, meaning frost) and refers to the eruption of magmas derived from the partial melting of ice rather than silicate rocks. Triton's icy magma originates from a mixture of water-ice, methane, and probably ammonia. When partially melted, this mixture behaves just as molten rock does on Earth. In fact, upon reaching the surface these magmas can generate quiet outpourings of ice lavas, or even explosive eruptions. When volatiles are released instantaneously, an explosive eruptive column will generate the ice equivalent of volcanic ash. In 1989, *Voyager 2* detected active plumes on Triton that rose 8 kilometers above the surface and were blown downwind for more than 100 kilometers. In other environments ice lavas develop that can flow great distances from their source—not unlike the fluid basaltic flows on Hawaii.

Minor Members of the Solar System: Asteroids, Comets, Meteoroids, and Dwarf Planets

In the vast spaces separating the eight planets as well as the expanses that extend to the outer reaches of the solar system are countless small chunks of debris, ranging from several hundred kilometers in diameter down to minute grains of dust. The objects found in this vast interplanetary space include *asteroids, comets, meteoroids,* and *dwarf planets.* Asteroids and meteoroids are fragments of rocky and metallic material with compositions somewhat like the terrestrial planets. They are distinguished from each other on the basis of size—those larger than 100 meters are asteroids, whereas anything smaller is a meteoroid. By contrast, comets are predominantly ices, with only small amounts of rocky material. The newest class of solar-system objects—dwarf planets—

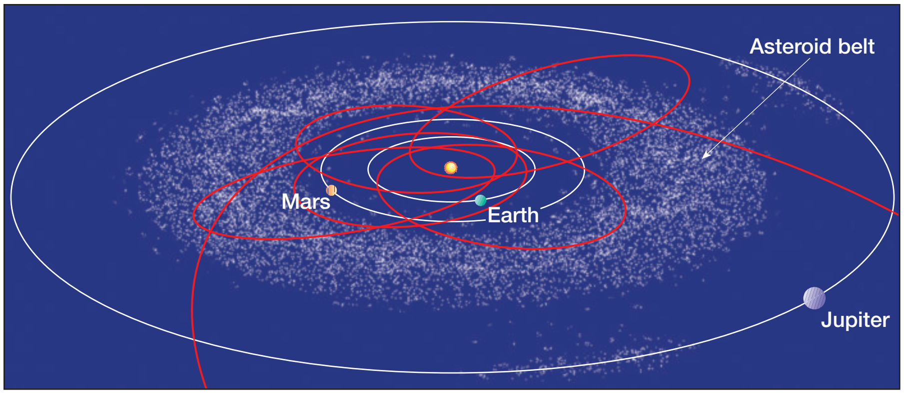


FIGURE 24.25 The orbits of most asteroids lie between Mars and Jupiter. Also shown are the orbits of a few known near-Earth asteroids. Perhaps a thousand or more asteroids have near-Earth orbits. Luckily, only a few dozen are thought to be larger than 1 kilometer in diameter.

includes Ceres, the largest known asteroid, and Pluto, which is thought to have a composition similar to Neptune's icy moon, Triton.

Asteroids: Planetesimals

Asteroids are small fragments (planetesimals) about 4.5 billion years old left over from the formation of the solar system. Most asteroids have a lower density than was first thought. This suggests that asteroids are porous bodies and not solid rocky or metallic objects, but more like a "rubble pile" of fragments bound together by gravity. The largest asteroid, Ceres, is 940 kilometers in diameter, but most of the 100,000 known asteroids are much smaller.

Most asteroids lie roughly midway between the orbits of Mars and Jupiter in the region known as the **asteroid belt** (Figure 24.25). Some travel along eccentric orbits that take them very near the Sun, and a few larger ones regularly pass close to Earth and the Moon. Many of the recent large impact craters on the Moon and Earth were probably the result of collisions with asteroids. About 2000 Earth-crossing asteroids are known, one-third of which are more than one kilometer in diameter. Inevitably, future Earth–asteroid collisions will occur (see Box 24.2).

Because most asteroids have irregular shapes, planetary geologists first speculated that they might be fragments of a broken planet that once orbited between Mars and Jupiter (Figure 24.25). However, the total mass of the asteroids is estimated to be only 1/1000 that of Earth, which itself is not a large planet. Today, most researchers agree that asteroids are the leftover debris from the solar nebula. Because of their location near Jupiter, with its huge gravitational field that continuously disrupted their motion, these planetesimals never accreted into a planet.

In February 2001 an American spacecraft became the first visitor to an asteroid. Although it was not designed for landing, *NEAR Shoemaker* landed successfully and generated information that has planetary geologists 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 (Figure 24.26). Researchers unexpectedly discovered that fine debris tends to concentrate in the low areas where it forms flat deposits that resemble 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 causes the boulders to move upward as the finer material sinks. This is analogous to what happens when a can of mixed nuts is shaken—the larger nuts rise to the top while the smaller pieces settle to the bottom.

Indirect evidence from meteorites suggests asteroids might retain much of the heat generated from impact events. Some may even have completely melted, which would cause them to differentiate into a dense iron and nickel core, and a rocky mantle. In November 2005, a Japanese probe, *Hayabusa,* landed on a small near-Earth asteroid named 25143 Itokawa and is scheduled to return samples to Earth by June 2010.

Comets: Dirty Snowballs

Comets, like asteroids, are also left over from the formation of the solar system. Unlike asteroids, comets are composed of ices (water, ammonia, methane, carbon dioxide, and

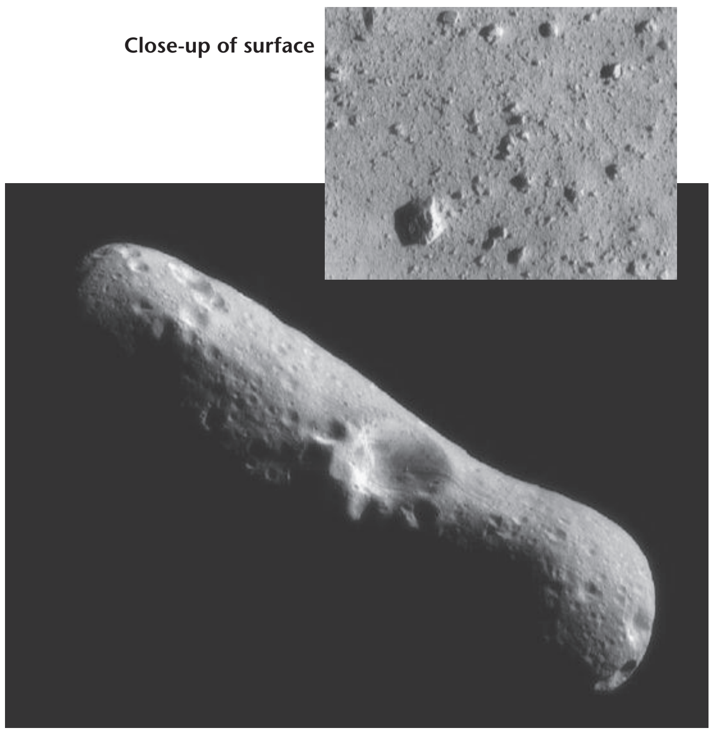


FIGURE 24.26 Image of asteroid Eros obtained by the *NEAR-Shoemaker* probe. Inset shows a close-up of Eros' barren rocky surface. (Courtesy of NASA)

BOX 24.2 ▶ EARTH AS A SYSTEM

Is Earth on a Collision Course?

The solar system is cluttered with meteoroids, asteroids, active comets, and extinct comets. These fragments travel at great speeds and can strike Earth with an explosive force many times greater than a powerful nuclear weapon.

In recent decades, it has become increasingly clear that comets and asteroids collide with Earth far more frequently than was previously known. The evidence is the 100 or so giant impact structures that have been identified (Figure 24.B). (Many impact craters were once mistaken for volcanic structures.) Most impact structures are so old and heavily eroded that they were discovered using satellite photography (Figure 24.C). One notable exception is a very fresh-looking crater near Winslow, Arizona, known as Meteor Crater (Figure 24.31). Note that this crater was produced by a meteorite perhaps only 50 meters in diameter.

About 65 million years ago a large asteroid about 10 kilometers (6 miles) in diameter collided with Earth off the Yucatan peninsula in Mexico. This impact is thought to have caused the demise of the dinosaurs, as well as the extinction of nearly 50 percent of all plant and animal species (see more on this in Chapter 22 *Earth's Evolution through Geologic Time*).

More recently, a spectacular explosion has been attributed to the collision of our planet with a comet or asteroid. In 1908, in a remote region of Siberia, a "fireball" that appeared more brilliant than the Sun exploded violently. The shock waves rattled windows and triggered reverberations heard up to 1000 kilometers away. The "Tunguska event," as it is called, scorched, delimbed, and flattened trees up to 30 kilometers from the epicenter. But expeditions to the area found no evidence of an impact crater or any metallic fragments. Evidently, the explosion, which equaled at least a 10-megaton nuclear bomb, occurred several kilometers above the surface. Why it exploded prior to impact is uncertain.

The dangers of living with these small but deadly objects from space again came to public attention in 1989 when an asteroid nearly 1 kilometer across shot past Earth. It was a near miss, about twice the distance to the Moon. Traveling at 70,000 kilometers (44,000 miles) per hour, it could have produced a crater 10 kilometers (6 miles) in diameter and perhaps 2 kilometers (1.2 miles) deep. As an observer noted, "Sooner or later it will be back." As it was, it crossed our orbit just six hours ahead of Earth. Statistics show that collisions of this magnitude should take place every few hundred million years and could have drastic consequences for life on Earth.

Scientists at NASA are tracking near-Earth objects (NEOS). When comets or asteroids pass close to any of the other planets, their orbits may be altered by the gravitational interaction, which may send them toward Earth. Currently, more than 800 asteroids with Earth-crossing orbits are being tracked.

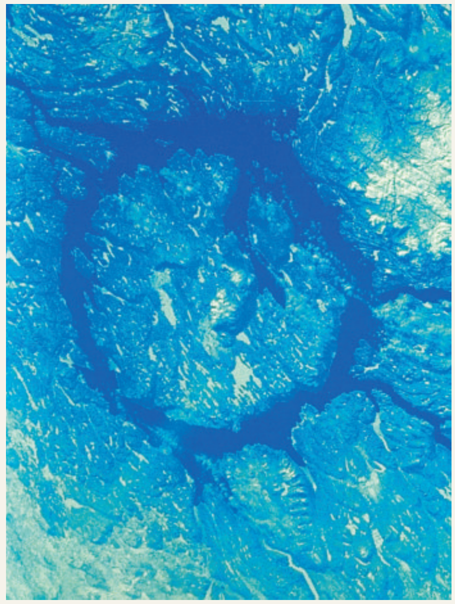


FIGURE 24.C Manicouagan, Quebec, is a 200-million-year-old eroded impact structure. The lake outlines the crater remnant, which is 70 kilometers (42 miles) across. Fractures related to this event extend outward for an additional 30 kilometers. (Courtesy of U.S. Geological Survey)

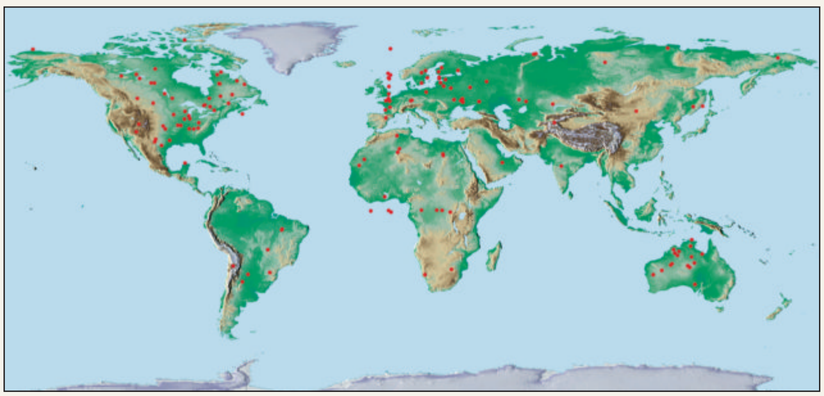


FIGURE 24.B World map of major impact structures. Others are being identified every year. (Data from Griffith Observatory)

carbon monoxide) that hold together small pieces of rocky and metallic materials, thus the nickname "dirty snowballs." Comets are among the most interesting and unpredictable bodies in the solar system. Many comets travel in very elongated orbits that carry them far beyond Pluto. These comets take hundreds of thousands of years to complete a single orbit around the Sun. However, a few *short-period comets* (those having orbital periods of less than 200 years), such as Halley's comet, make regular encounters with the inner solar system.

When first observed, a comet appears very small, but as it approaches the Sun, solar energy begins to vaporize the ices, producing a glowing head called the **coma** (Figure 24.27). The size of the coma varies greatly from one comet to another. Extremely rare ones exceed the size of the Sun, but most approximate the size of Jupiter. Within the coma, a small

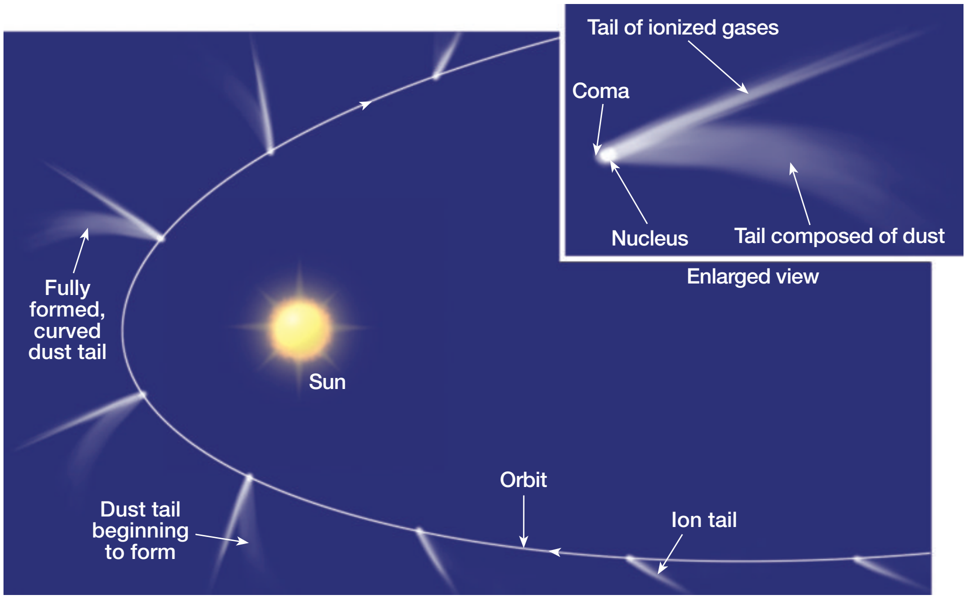


FIGURE 24.27 Orientation of a comet's tail as it orbits the Sun.

glowing nucleus with a diameter of only a few kilometers can sometimes be detected. As comets approach the Sun, some, but not all, develop a tail that extends for millions of kilometers. Despite the enormous size of their tails and comas, comets are relatively small members of the solar system.

The fact that the tail of a comet points away from the Sun in a slightly curved manner (Figure 24.27) led early astronomers to propose that the Sun has a repulsive force that pushes the particles of the coma away, thus forming the tail. Today, two solar forces are known to contribute to this formation. One, *radiation pressure*, pushes dust particles away from the coma. The second, known as *solar wind*, is responsible for moving ionized gases, particularly carbon monoxide. Sometimes a single tail composed of both dust and ionized gases is produced, but often two tails are observed (Figure 24.28).

As a comet moves 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 from the comet forever. Consequently, it is believed that most comets cannot survive more than a few hundred close orbits of the Sun. Once all the gases are expelled, the remaining material—a swarm of tiny metallic and stony particles—continues the orbit without a coma or a tail.

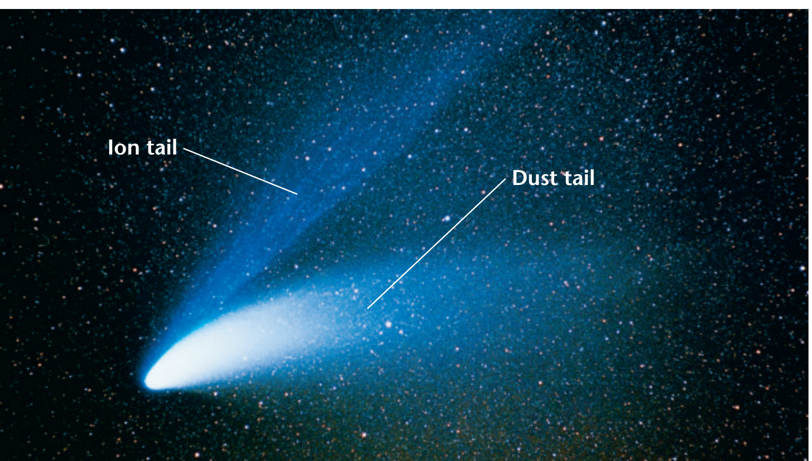
Most comets are found in two regions of the outer solar system. The short period comets are thought to orbit beyond Neptune in a region called the **Kuiper belt,** in honor of astronomer Gerald Kuiper, who had predicted their existence (Figure 24.29). (During the past decade, more than a hundred of these icy bodies have been discovered.) Like the asteroids in the inner solar system, most Kuiper belt comets move in nearly circular 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, may occasionally alter the orbit of a comet enough to send it to the inner solar system, and into our view.

Unlike Kuiper belt comets, long-period comets have orbits that are *not* confined to the plane of the solar system. These comets appear to be distributed in all directions from the Sun, forming a spherical shell around the solar system, called the **Oort cloud,** after the Dutch astronomer Jan Oort. Millions of comets are believed to orbit the Sun at distances greater than 10,000 times the Earth–Sun distance. The gravitational effect of a distant passing star is believed to 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.

But why are comets found in both the Kuiper belt and the Oort cloud? It appears that comets, like asteroids, are planetesimal bodies formed by accretion of material in the solar nebula. In other words, they are leftovers from the planetary formation process. In contrast to asteroids that formed in the inner solar system of mostly metallic and rocky materials, comets are icy planetesimals that formed in the region of the giant planets and beyond. The ones that formed beyond the orbit of Neptune and did not accrete into a large planetary body make up the Kuiper belt objects.

The icy planetesimals of the Oort cloud, on the other hand, are thought to have formed in the region of the Jovian planets. While the vast majority of icy objects would have accreted into protoplanets, some survived. Under the strong gravitational fields of the giants, their orbits would have been greatly altered. Some cometary objects would have been hurled toward the inner solar system where they collided with the terrestrial planets. The remainder were "thrown out" into space to form the Oort cloud located at the outermost reaches of the solar system.

FIGURE 24.28 Comet Hale-Bopp. The two tails seen in the photograph are between 10 million and 15 million miles long. (Peoria Astronomical Society photograph by Eric Clifton and Craig Neaveill)



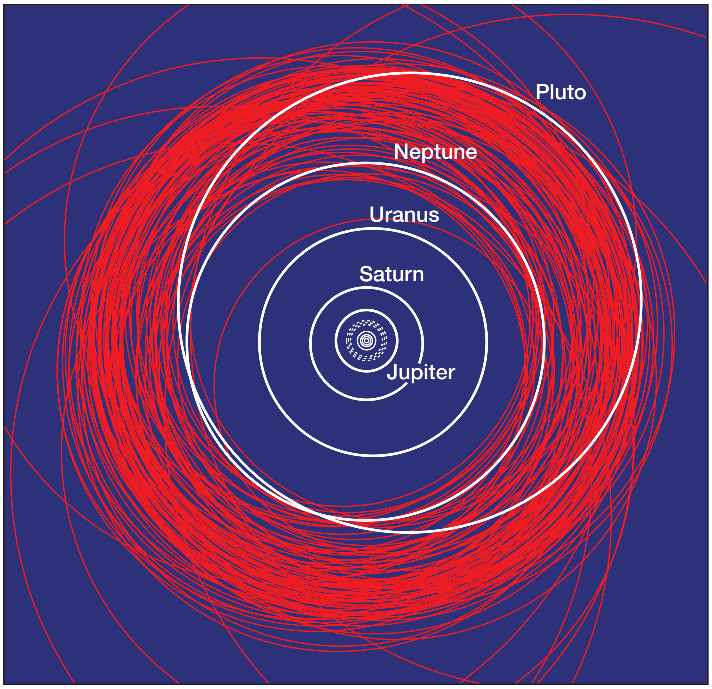


FIGURE 24.29 The orbits of some known Kuiper belt objects.

The most famous short-period comet is Halley's Comet. Its orbital period averages 76 years, and every one of its 29 appearances since 240 B.C. has been recorded by Chinese astronomers. This record is a testimonial to their dedication as astronomical observers and to the endurance of their culture. When seen in 1910, Halley's Comet had developed a tail nearly 1.6 million kilometers (1 million miles) long and was visible during the daytime.

In 1986 the unspectacular showing of Halley's Comet was a disappointment to many people in the Northern Hemisphere. Yet it was during this most recent visit to the inner solar system that a great deal of new information was learned about this most famous of comets. The new data were gathered by space probes sent to rendezvous with the comet. Most notably, the European probe *Giotto* approached to within 600 kilometers of the comet's nucleus and obtained the first close up images of comet structure.

We now know that the nucleus of Halley's Comet is potato-shaped and 16 by 8 kilometers in size. The surface is irregular and full of craterlike pits. Gases and dust that escape from the nucleus to form the coma and tail appear to gush from its surface as bright jets or streams. Only about 10 percent of the comet's total surface was emitting these jets at the time of the rendezvous. The remaining surface area of the comet appeared to be covered with a dark layer that may be organic material.

In 1997 the comet Hale-Bopp made for spectacular viewing around the globe. As comets go, the nucleus of Hale-Bopp was unusually large, about 40 kilometers (25 miles) in diameter. As shown in Figure 24.28, two tails nearly 15 million miles long extended from this comet. The bluish gas-tail is composed of positively charged ions, and it points almost directly away from the Sun. The brighter tail is composed of dust and other rocky debris. Because the rocky material is more massive than the ionized gases, it is less affected by the solar wind and follows a different trajectory away from the comet.

Meteoroids: Visitors to Earth

Nearly everyone has seen a **meteor,** popularly (but inaccurately) called a "shooting star." This streak of light lasts from an eyeblink to a few seconds and occurs when a small solid particle, a **meteoroid,** enters Earth's atmosphere from interplanetary space. Friction between the meteoroid and the air heats both and produces the light we see. Most meteoroids originate from any one of the following three sources: (1) interplanetary debris that was not gravitationally swept up by the planets during the formation of the solar system, (2) material that is continually being lost from the asteroid belt, or (3) the solid remains of comets that once passed through Earth's orbit. A few meteoroids are believed to be fragments of the Moon, or possibly Mars, that were ejected when an asteroid impacted these bodies.

Meteoroids less than about a meter in diameter generally vaporize before reaching Earth's surface. Some, called *micrometeorites*, are so tiny that their rate of fall becomes too slow to cause them to burn up, so they drift down as space dust. Each day, the number of meteoroids that enter Earth's atmosphere must reach into the thousands. After sunset on a clear night, a half dozen or more are bright enough to be seen with the naked eye each hour from anywhere on Earth.

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 and 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 24.2). Some swarms not associated with the orbits of known comets are probably the remains of the nucleus of a long-defunct comet. The notable Perseid meteor shower that occurs each year around

TABLE 24.2 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	

FIGURE 24.30 Iron meteorite found near Meteor Crater, Arizona. (Courtesy of Meteor Crater Enterprises, Inc.)

August 12 is believed to be the remains of the Comet 1862 III, which has a period of 110 years.

Meteoroids that are the remains of comets tend to be small and only occasionally reach the ground. Most meteoroids large enough to survive the heated fall are thought to originate among the asteroids, where chance collisions modify their orbits and send them toward Earth. Earth's gravity does the rest.

The remains of meteoroids, when found on Earth, are referred to as **meteorites** (Figure 24.30). A few very large meteoroids have blasted out craters on Earth's surface that strongly resemble those on the lunar surface. The most famous is Meteor Crater in Arizona (Figure 24.31). This huge cavity is about 1.2 kilometers (0.75 miles) across, 170 meters (560 feet) deep, and has an upturned rim that rises 50 meters (165 feet) above the surrounding countryside. Over 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, the impact likely occurred within the last 50,000 years.

Prior to the Moon rocks brought back by lunar explorers, meteorites were the only extraterrestrial materials that could be directly examined (Figure 24.30). Meteorites are classified by their composition: (1) *irons*, mostly iron with 5 percent to 20 percent nickel; (2) *stony* silicate minerals with inclusions of other minerals; and (3) *stony-irons* mixtures. Although stony meteorites are much more common, people tend to find irons. This is understandable because metallic meteorites withstand the impact better, weather more slowly, and are much easier for a layperson to distinguish from terrestrial rocks. Iron meteorites are probably fragments of once-molten cores of large asteroids or small planets.

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

FIGURE 24.31 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 meteoroids and other objects that can strike Earth with explosive force. (Photo by Michael Collier)

FIGURE 24.32 Pluto, a dwarf planet compared to some large Kuiper belt objects. The Earth–Moon system and Neptune's moon, Triton, added for scale. (Courtesy of NASA)

If meteorites represent the makeup of Earth-like planets, as some planetary geologists suggest, then Earth must contain a much larger percentage of iron than is indicated by surface rocks. This is one reason that geologists suggest that Earth's core must be mostly iron and nickel. In addition, radiometric dating of meteorites indicates that our solar system's age certainly exceeds 4.5 billion years. This "old age" has been confirmed by data obtained from lunar samples.

Dwarf Planets

Since Pluto's discovery in 1930, it has been a mystery on the edge of the solar system. At first, Pluto was thought to be about as large as Earth, but as better images were obtained, Pluto's diameter was estimated to be a little less than one half that of Earth. Then, in 1978, astronomers discovered that Pluto has a satellite (Charon), whose brightness combined with its parent made Pluto appear much larger than it really was (Figure 24.32). Recent images obtained by the *Hubble Space Telescope* established the diameter of Pluto at only 2300 kilometers (1425 miles). This is about one-fifth that of Earth and less than half that of Mercury, long considered the runt of the solar system. In fact, seven moons, including Earth's moon, are larger than Pluto.

Even more attention was given to Pluto's status as a planet when in 1992 astronomers discovered another icy body in orbit beyond Neptune. Soon hundreds of these *Kuiper belt objects* were discovered forming a band of small objects, similar to the asteroid belt between Mars and Jupiter. However, these orbiting bodies are made up of dust and ices, like comets, rather than metallic and rocky substances, like asteroids. Many other planetary objects, some larger than Pluto, are thought to exist in this belt of icy worlds found beyond the orbit of Neptune.

The International Astronomical Union, a group that has the power to determine whether or not Pluto is a planet, voted August 24, 2006, to add a new class of planets called **dwarf planets.** These include celestial bodies that orbit around the Sun, are essentially round due to their self-gravity, but are not the only objects to occupy their area of space. By this definition, Pluto is recognized as a dwarf planet and the prototype of a new category of planetary objects. Other dwarf planets include 2003 UB313, a Kuiper Belt object, and Ceres, the largest known asteroid.

This is not the first time a planet has been demoted. In the mid-1800s astronomy textbooks listed as many as 11 planets in our solar system, including the asteroids Vesta, Juno, Ceres, and Pallas. Soon astronomers discovered dozens of other "planets," which made it clear that these small bodies represent another class of objects separate from the planets. Consequently, the number of major planets fell to eight. (Neptune had just been discovered, but Pluto's discovery did not occur until 1930.)

It is now clear that Pluto was unique among the classical planets, being very different from the four rocky innermost planets, and unlike the four gaseous giants. With the new classification, astronomers believe hundreds of additional dwarf planets might be found. *New Horizons*, the first spacecraft to explore the outer solar system, was launched in January 2006. It is scheduled to fly by Pluto in July 2015 and continue on to explore the Kuiper Belt.

Summary

- The planets can be arranged into two groups: the *terrestrial* (Earth-like) *planets* (Mercury, Venus, Earth, and Mars) and the *Jovian* (Jupiter-like) *planets* (Jupiter, Saturn, Uranus, and Neptune). *When compared to the Jovian planets, the terrestrial planets are smaller, more dense, contain proportionally more rocky material, have slower rates of rotation, and meager atmospheres..*
- The lunar surface exhibits several types of features. *Impact craters* were produced by the collision of rapidly moving interplanetary debris (*meteoroids*). Bright, densely cratered *highlands* make up most of the lunar surface. The dark, fairly smooth lowlands are called *maria.* Maria basins are enormous impact craters that were later flooded with layer upon layer of very fluid basaltic lava. All lunar terrains are mantled with a soil-like layer of gray, unconsolidated debris, called *lunar regolith,* which has been derived from a few billion years of meteroic bombardment. One hypothesis for the Moon's origin suggests that a Mars-sized object collided with Earth to produce the Moon. Scientists conclude that the *lunar surface evolved in four stages:* (1) *the original crust (highlands),* (2) *the highlands,* (3) *maria basins,* and (4) *youthful rayed craters.*
- *Mercury* is a small, dense planet that has virtually no atmosphere and exhibits the greatest temperature extremes of any planet. *Venus,* the brightest planet in the sky, has a thick, heavy atmosphere composed of 97 percent carbon dioxide, a surface of relatively subdued plains and inactive volcanic features, a surface atmospheric pressure 90 times that of Earth's, and surface temperatures of 475°C (900°F). *Mars,* the Red Planet, has a carbon dioxide atmosphere only 1 percent as dense as Earth's, extensive dust storms, numerous inactive volcanoes, many large canyons, and several valleys of debatable origin exhibiting drainage patterns similar to stream valleys on Earth. *Jupiter,* the largest planet, rotates rapidly, has a banded appearance caused by huge convection currents driven by the planet's interior heat, a *Great Red Spot* that varies in size, a thin ring system, and at least 63 moons (one of the moons, *Io,* is perhaps the most volcanically active body in the solar system). *Saturn* is best known for its system of rings. It also has a dynamic atmosphere with winds up to 930 miles per hour and storms similar to Jupiter's Great Red Spot. *Uranus* and *Neptune* are often called "the twins" because of their similar structure and composition. A unique feature of Uranus is the fact that it rotates on its side. Neptune has white, cirruslike clouds above its main cloud deck and an Earth-size *Great Dark Spot,* assumed to be a large rotating storm similar to Jupiter's Great Red Spot.
- The minor members of the solar system include *asteroids, comets, meteoroids,* and *dwarf planets.* Most asteroids lie between the orbits of Mars and Jupiter. Asteroids are leftover rocky and metallic debris from the solar nebula that never accreted into a planet. Comets are made of ices (water, ammonia, methane, carbon dioxide, and carbon monoxide) with small pieces of rocky and metallic material. Many travel in very elongated orbits that carry them beyond Pluto. Meteoroids, small solid particles that travel through interplanetary space, become *meteors* when they enter Earth's atmosphere and vaporize with a flash of light. *Meteor showers* occur when Earth encounters a swarm of meteoroids, probably material lost by a comet. *Meteorites* are the remains of meteoroids found on Earth. Recently, Pluto was placed into a new class of solar system objects called *dwarf planets.*

Review Questions

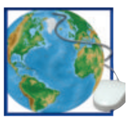
1. By what criteria are the planets placed into either the Jovian or terrestrial group?
2. What are the three types of materials thought to make up the planets? How are they different? How does their distribution account for the density differences between the terrestrial and Jovian planetary groups?
3. Explain why the terrestrial planets have meager atmospheres, as compared to the Jovian planets.
4. How is crater density used in the relative dating of features on the Moon?
5. Briefly outline the history of the Moon.
6. How are the maria of the Moon thought to be similar to the Columbia Plateau?
7. Venus has been referred to as "Earth's twin." In what ways are these two planets similar? How do they differ?
8. What surface features does Mars have that are also common on Earth?
9. Why are the largest volcanoes on Earth so much smaller than the largest ones on Mars?
10. Why might astrobiologists be intrigued by evidence that groundwater has seeped onto the surface of Mars?
11. The two "moons" of Mars were once suggested to be artificial. What characteristics do they have that would cause such speculation?
12. What is the nature of Jupiter's Great Red Spot?
13. Why are the Galilean satellites of Jupiter so named?
14. What is distinctive about Jupiter's satellite Io?
15. Why are the *outer* satellites of Jupiter thought to have been captured rather than having been formed with the rest of the satellite system?

16. How are Jupiter and Saturn similar?
17. What two roles do ring moons play in the nature of planetary ring systems?
18. How are Saturn's satellite Titan and Neptune's satellite Triton similar?
19. Name three bodies in the solar system that exhibit active volcanism.
20. Where are most asteroids found?
21. What do you think would happen if Earth passed through the tail of a comet?
22. Where are most comets thought to reside? What eventually becomes of comets that orbit close to the Sun?
23. Compare meteoroid, meteor, and meteorite.
24. What are the three main sources of meteoroids?
25. 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?
26. It has been estimated that Halley's Comet has a mass of 100 billion tons. Further, this comet is estimated to lose 100 million tons of material during the few months that its orbit brings it close to the Sun. With an orbital period of 76 years, what is the maximum remaining life span of Halley's Comet?

Key Terms

asteroids (p. 674)
asteroid belt (p. 674)
coma (p. 675)
comet (p. 674)
cryovolcanism (p. 673)
dwarf planet (p. 679)
escape velocity (p. 658)
highlands (p. 659)
inner planet (p. 657)
impact craters (p. 660)
Jovian planet (p. 657)
Kuiper belt (p. 676)
lunar regolith (p. 661)
maria (p. 659)
meteor (p. 677)
meteorite (p. 678)
meteoroid (p. 677)
meteor shower (p. 677)
Oort cloud (p. 676)
outer planet (p. 657)
planetesimals (p. 657)
protoplanets (p. 657)
solar nebula (p. 657)
terrae (p. 659)
terrestrial planet (p. 657)

Web Resources



The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

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