THE MOON AND MERCURY

SCORCHED AND BATTERED WORLDS

LEARNING GOALS

Studying this chapter will enable you to

1. Specify the general characteristics of the Moon and Mercury, and compare them with those of Earth.
2. Describe the surface features of the Moon and Mercury, and recount how those two bodies were formed by events early in their history.
3. Explain how the Moon's rotation is influenced by its orbit around Earth and Mercury's by its orbit around the Sun.
4. Explain how observations of cratering can be used to estimate the age of a body's surface.
5. Describe the evidence for ancient volcanism on the Moon and Mercury.
6. Compare the Moon's interior structure with that of Mercury.
7. Summarize the leading theory of the formation of the Moon.
8. Discuss how astronomers have pieced together the story of the Moon's evolution, and compare its evolutionary history with that of Mercury.

THE BIG PICTURE Although the Moon is the closest astronomical object to Earth, it is remarkably unlike our own planet. The Moon actually has much more in common with Mercury, the planet closest to the Sun.

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The Moon is Earth's only natural satellite. Mercury, the smallest terrestrial world, is the planet closest to the Sun. Despite their different environments, these two bodies have many similarities—indeed, at first glance, you might even mistake one for the other. Both have heavily cratered, ancient surfaces, littered with boulders and pulverized dust. Both lack atmospheres to moderate day-to-night variations in solar heating and experience wild temperature swings as a result. Both are geologically dead.

In short, the Moon and Mercury differ greatly from Earth, but it is precisely those differences that make these desolate worlds so interesting to planetary scientists. Why is the Moon so unlike our own planet, despite its nearness to us, and why does planet Mercury apparently have so much more in common with Earth's Moon than with Earth itself? In this chapter, we explore the properties of these two worlds as we begin our comparative study of the planets and moons that make up our solar system.

LEFT: *America's manned exploration of the Moon was arguably the greatest engineering feat of the 20th century, perhaps one of the greatest of all time. Nine crewed missions were launched to the Moon, a dozen astronauts were landed, and all returned safely to Earth. Here, an Apollo 16 astronaut is prospecting near the rim of Plum Crater for rock samples that might help reveal the origin of the Moon. The "rover" that carried him several kilometers from his landing craft can be seen in the left background. Given the lack of wind and water on the Moon, the bootprints in the foreground are destined to survive for more than a million years. (NASA)*

8.1 Orbital Properties

We begin our study of the Moon and Mercury by examining their orbits. This knowledge will, in turn, aid us in determining and explaining the other properties of these worlds.

The Moon

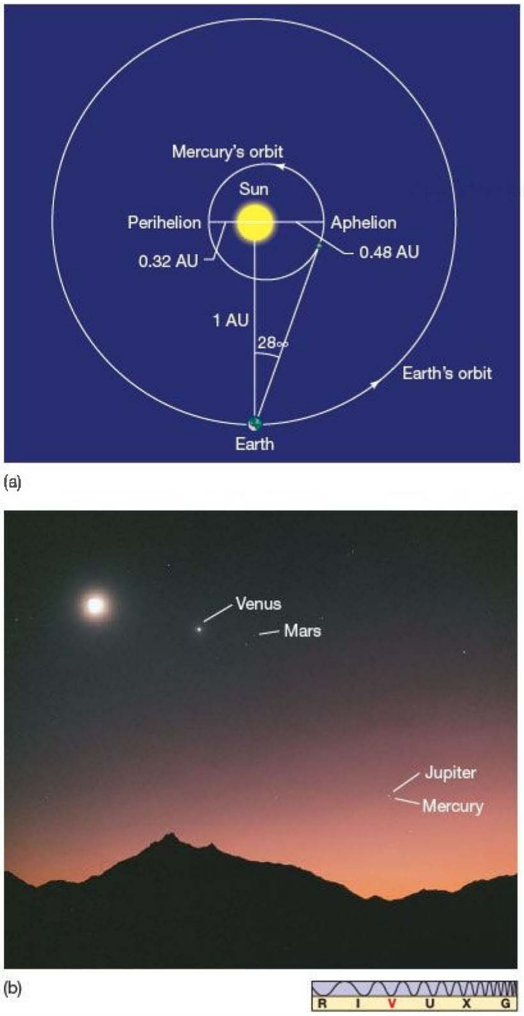
Parallax methods, described in Chapter 1, can provide us with quite accurate measurements of the distance to the Moon, using Earth's diameter as a baseline. ∞ (Sec. 1.6) Radar ranging yields more accurate distances. The Moon is much closer than any of the planets, and the radar echo bounced off the Moon's surface is strong. A radio telescope receives the echo after a round trip of 2.56 seconds. Dividing this time by 2 and multiplying it by the speed of light (300,000 km/s) gives us a distance of 384,000 km. (The actual distance at any particular time depends on the Moon's location in its slightly elliptical orbit around Earth.)

Current laser-ranging technology, using reflectors placed on the lunar surface by *Apollo* astronauts (see *Discovery 8-1*) to reflect laser beams fired from Earth, allows astronomers to measure the round-trip time with submicrosecond accuracy. Repeated measurements have allowed astronomers to determine the Moon's orbit to within a few centimeters. This precision is necessary for programming unmanned spacecraft to land successfully on the lunar surface.

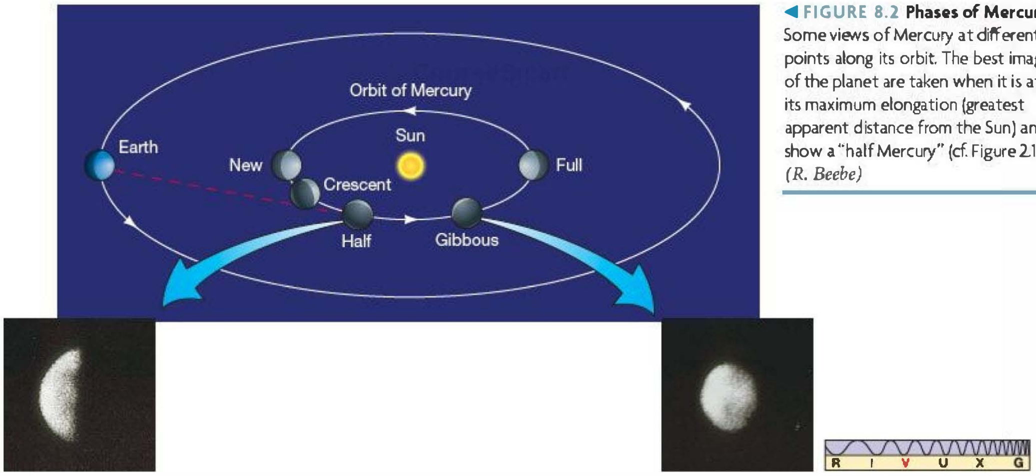
Mercury

Viewed from Earth, Mercury never strays far from the Sun. As illustrated in Figure 8.1(a), the planet's 0.4-AU orbital semimajor axis means that its angular distance from the Sun never exceeds 28°. Consequently, the planet is visible to the naked eye only when the Sun's light is blotted out—just before dawn or just after sunset (or, much less frequently, during a total solar eclipse)—and it is not possible to follow Mercury through a full cycle of phases. In fact, although Mercury was well known to ancient astronomers, they originally believed that this companion to the Sun was two different objects, and the connection between the planet's morning and evening appearances took some time to establish. However, later Greek astronomers were certainly aware that the "two planets" were really different alignments of a single body. Figure 8.1(b), a photograph taken just after sunset, shows Mercury above the western horizon, along with three other planets and the Moon.

Because Earth rotates at a rate of 15° per hour, Mercury is visible for at most 2 hours on any given night, even under the most favorable circumstances. For most observers at most times of the year, Mercury is generally visible for a much shorter period. Nowadays, large telescopes can filter out the Sun's glare and observe Mercury even during the daytime, when the planet is higher in the



▲ FIGURE 8.1 **Evening Sky** (a) Mercury's orbit has a semimajor axis of just 0.4 AU, so the planet can never be farther than 28° from the Sun, as seen from Earth. Mercury's eccentric orbit means that this maximum separation is achieved only for the special configuration shown here, in which the Earth–Sun line is perpendicular to the long axis of Mercury's orbit and Mercury is near aphelion (its greatest distance from the Sun). (b) Four planets, together with the Moon, are visible in this photograph taken shortly after sunset. To the right of the Moon (top left) is the brightest planet, Venus. A little farther to the right is Mars, with the star Regulus just below and to its left. At the lower right, at the edge of the Sun's glare, are Jupiter and Mercury. (The Moon appears round rather than crescent shaped because the "dark" portion of its disk is indirectly illuminated by sunlight reflected from Earth. This "earthshine," relatively faint to the naked eye, is exaggerated in the overexposed photographic image.) *(J. Sanford/Photo Researchers, Inc.)*



◀ **FIGURE 8.2 Phases of Mercury** Some views of Mercury at different points along its orbit. The best images of the planet are taken when it is at its maximum elongation (greatest apparent distance from the Sun) and show a "half Mercury" (cf. Figure 2.12a). *(R. Beebe)*

sky and atmospheric effects are reduced. (The amount of air that the light from the planet has to traverse before reaching our telescope decreases as the height of the planet above the horizon increases.) In fact, some of the best views of Mercury have been obtained in this way. The naked-eye or amateur astronomer is generally limited to nighttime observations, however.

In all cases, it becomes progressively more difficult to view Mercury the closer (in the sky) its orbit takes it to the Sun. The best images of the planet therefore show a "half Mercury," close to its maximum angular separation from the Sun, or *maximum elongation,* as illustrated in Figure 8.2. (A planet's *elongation* is just its angular distance from the Sun, as seen from Earth.)

8.2 Physical Properties

From Earth, the Moon's angular diameter is about 0.5°. Knowing that and the distance to the Moon, we can easily calculate our satellite's true size, as discussed in Chapter 1. ∞ *(More Precisely 1-2)* The Moon's radius is about 1700 km, roughly one-fourth that of Earth. More precise measurements yield a lunar radius of 1738 km. We can determine Mercury's radius by similar reasoning. At its closest approach to Earth, at a distance of about 0.52 AU, Mercury's angular diameter is measured to be 13″ (arc seconds), implying a radius of about 2450 km, or 0.38 of Earth's radius. More accurate measurements by unmanned space probes yield a result of 2440 km.

As mentioned in Chapter 6, even before the Space Age, the masses of both the Moon and Mercury were already quite well known from studies of their effects on Earth's orbit. ∞ (Sec. 6.2) The mass of the Moon is 7.3×10^{22} kg, approximately one-eightieth (0.012) the mass of Earth. The mass of Mercury is 3.3×10^{23} kg—about 0.055 Earth mass.

The Moon's average density of 3300 kg/m^3 contrasts with the average Earth value of about 5500 kg/m^3, suggesting that the Moon contains fewer heavy elements (such as iron) than Earth does. In contrast, despite its many other similarities to the Moon, Mercury's mean density is 5400 kg/m^3, only slightly less than that of Earth. Assuming that surface rocks on Mercury are of similar density to surface rocks on Earth and the Moon, we are led to the conclusion that the interior of Mercury must contain a lot of high-density material, most probably iron. In fact, since Mercury is considerably less massive than Earth, its interior is squeezed less by the weight of overlying material, so Mercury's iron core must actually contain a much larger fraction of the planet's mass than does our own planet's core. ∞ (Sec. 6.2)

Because the Moon and Mercury are so much less massive than Earth, their gravitational fields are also weaker. The force of gravity on the lunar surface is only about one-sixth that on Earth; Mercury's surface gravity is a little stronger—about 0.4 times Earth's. Thus, an astronaut weighing 180 lb on Earth would weigh a mere 30 lb on the Moon and 72 lb on Mercury. Those bulky space suits used by the *Apollo* astronauts on the Moon were not nearly as heavy as they appeared!

Astronomers have never observed any appreciable atmosphere on the Moon or Mercury, either spectroscopically from Earth or during close approaches by spacecraft. This is a direct consequence of these bodies' weak gravitational fields, as discussed in *More Precisely 8-1* (p. 192). Simply put, a massive object has a better chance of retaining an atmosphere because the more massive an object is, the larger is the speed needed for atoms or molecules to escape from

ANIMATION/VIDEO Transit of Mercury

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the object's gravitational pull. The Moon's escape speed is only 2.4 km/s, compared with 11.2 km/s for Earth; Mercury's escape speed is 4.2 km/s. Any primary atmospheres these worlds had initially, or secondary atmospheres that appeared later, are gone forever. ∞ (Sec. 7.2)

During its flybys of Mercury in 1974 and 1975, the U.S. space probe *Mariner 10* found traces of what was at first thought to be an atmosphere on the planet. ∞ (Sec. 6.6) However, this gas is now known to be temporarily trapped hydrogen and helium "stolen" from the solar wind by the planet's gravity. Mercury captures this gas and holds it for just a few weeks before it leaks away again into space. More recently, NASA's *Messenger* probe measured the composition of the gas during its first of three flybys in 2008 (before going into orbit around Mercury in 2011) and found that, while indeed composed largely of hydrogen and helium like the Sun, its gas also contains more massive atoms of sodium, potassium, and magnesium. In fact, both the Moon and Mercury have extremely tenuous atmospheres (less than a trillionth the density of Earth's atmosphere) of such relatively heavy atoms. Scientists think that these atoms have been kicked off the surface by interactions with the solar wind; they do not constitute a true atmosphere in any sense. Thus, neither the Moon nor Mercury has any protection against the harsh environment of interplanetary space. This fact is crucial in understanding their surface evolution and present-day appearance.

Lacking the moderating influence of an atmosphere, both the Moon and Mercury are characterized by wide variations in surface temperature. Noontime temperatures at the Moon's equator can reach 400 K, well above the boiling point of water. Because of its proximity to the Sun, Mercury's daytime temperature is even higher—radio observations of the planet's thermal emissions indicate that it can reach 700 K. ∞ (Sec. 3.4) But at night or in the shade, temperatures on both worlds fall to about 100 K, well below water's freezing point. Mercury's 600-K temperature range is the largest of any planet or moon in the solar system.

CONCEPT CHECK

✔ Why do the Moon and Mercury have no significant atmospheres, unlike Earth?

8.3 Surface Features on the Moon and Mercury

Lunar Terrain

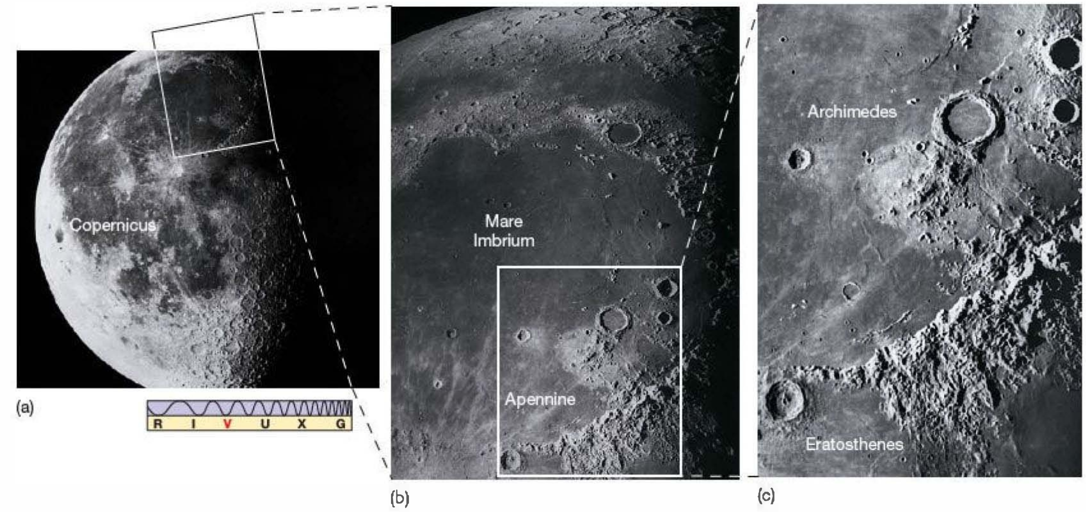
The first observers to point their telescopes at the Moon—most notable among them Galileo Galilei—saw large dark areas resembling (they thought) Earth's oceans. They also saw light-colored areas resembling the continents. Both types of regions are clear in Figure 8.3, a *mosaic* (a composite image constructed from many individual photographs) of the full Moon. The light and dark surface features are also evident to the naked eye, creating the face of the familiar "man in the Moon."

▲ FIGURE 8.3 **Full Moon, Near Side** A photographic mosaic of the full Moon, north pole at the top. Because the Moon emits no visible radiation of its own, we can see it only by the reflected light of the Sun. Some prominent maria are labeled. *(UC/Lick Observatory)*

Today we know that the dark areas are not oceans, but extensive flat areas that resulted from lava flows during a much earlier period of the Moon's evolution. Nevertheless, they are still called **maria**, a Latin word meaning "seas" (singular: *mare*). There are 14 maria, all roughly circular. The largest of them (Mare Imbrium) is about 1100 km in diameter. The lighter areas, originally dubbed *terrae*, from the Latin word for "land," are now known to be elevated several kilometers above the maria. Accordingly, they are usually called the lunar **highlands**.

The smallest lunar features we can distinguish with the naked eye are about 200 km across. Telescopic observations further resolve the surface into numerous bowl-shaped depressions, or **craters** (after the Greek word for "bowl"). Most craters apparently formed eons ago, primarily as the result of meteoritic impact. In Figures 8.4(a) and (b), craters are particularly clear near the *terminator* (the line that separates day from night on the surface), where the Sun is low in the sky and casts long shadows that enable us to distinguish quite small surface details.

Due to the blurring effects of our atmosphere, the smallest lunar objects that telescopes on Earth's surface can resolve are about 1 km across (see Figure 8.4c). Much more

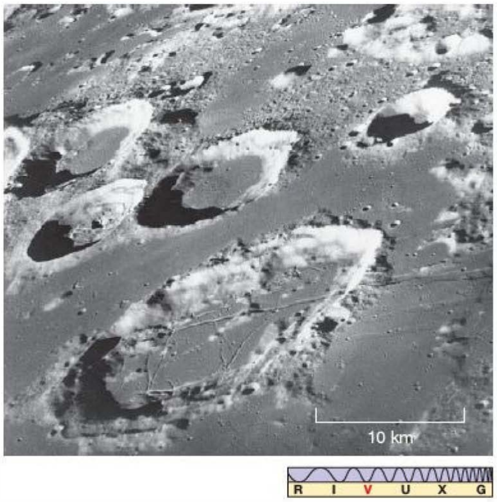


▲ **FIGURE 8.4 Moon, Close Up** (a) The Moon near third quarter. Surface features are much more visible near the *terminator*, the line separating light from dark, where sunlight strikes at a sharp angle and shadows highlight the landscape. (b) Magnified view of a region near the terminator, as seen from Earth through a large telescope. The central dark area is Mare Imbrium, ringed at the bottom by the Apennine mountains. (c) Enlargement of a portion of (b). The smallest craters visible here have diameters of about 2 km, about twice the size of the Barringer crater on Earth shown in Figure 8.18. *(UC/Lick Observatory; Palomar)*

ANIMATION/VIDEO Full Rotation of Moon

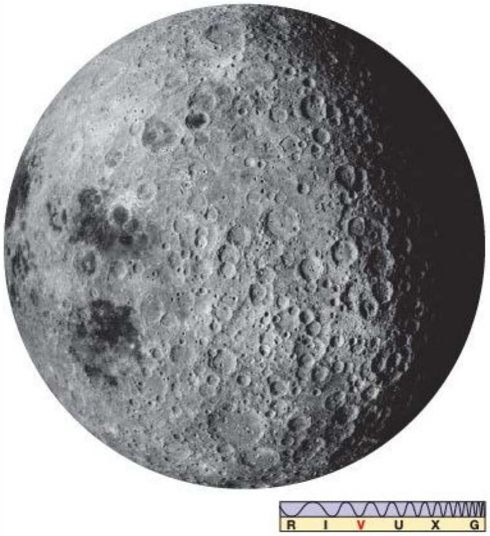
detailed photographs have been taken by orbiting spacecraft and, of course, by visiting astronauts. Figure 8.5 is a view of some lunar craters taken from an orbiting spacecraft, showing features as small as 500 m across. Craters are found everywhere on the Moon's surface, although they are much more prevalent in the highlands. They come in all sizes—the largest are hundreds of kilometers in diameter; the smallest are microscopic.

Based on studies of lunar rock brought back to Earth by *Apollo* astronauts and unmanned Soviet landers, geologists have identified important differences in both *composition* and *age* between the highlands and the maria. The highlands are made largely of rocks rich in aluminum, making them lighter in color and lower in density (2900 kg/m^3) than the material in the maria, which contains more iron, giving it a darker color and greater density (3300 kg/m^3). Loosely speaking, the highlands represent the Moon's crust, whereas the maria are made of mantle material. Maria rock is quite similar to terrestrial basalt, and geologists think that it arose on the Moon much as basalt did on Earth, from the upwelling of molten material through the crust. ∞ (Sec. 7.3) Radioactive dating indicates ages of 4 to 4.4 billion years for highland rocks and from 3.2 to 3.9 billion years for those from the maria. ∞ *(More Precisely 7-2)*



◀ **FIGURE 8.5 Moon from Apollo** The Moon, as seen from the *Apollo 8* orbiter during the first human circumnavigation of our satellite in 1968. Craters ranging in size from 50 km to 500 m (also the width of the long fault lines) can be seen. *(NASA)*

ANIMATION/VIDEO Lunar Flyby



▲ FIGURE 8.6 **Full Moon, Far Side** The far side of the Moon, as photographed by the *Apollo 16* manned mission. The large, dark region at center bottom outlines the South Pole–Aitken Basin, the largest and deepest impact basin known in the solar system. Only a few small maria exist on the far side. *(NASA)*

All of the Moon's significant surface features have names. The 14 maria bear fanciful Latin names—Mare Imbrium ("Sea of Showers"), Mare Nubium ("Sea of Clouds"), Mare Nectaris ("Sea of Nectar"), and so on. Most mountain ranges in the highlands bear the names of terrestrial mountain ranges—the Alps, the Carpathians, the Apennines, the Pyrenees, and so on. Most of the craters are named after great scientists or philosophers, such as Plato, Aristotle, Eratosthenes, and Copernicus.

Because the Moon rotates once on its axis in exactly the same time it takes to complete one orbit around Earth, the Moon has a "near" side, which is always visible from Earth, and a "far" side, which never is (see Section 8.4). To the surprise of most astronomers, when the far side of the Moon was mapped, first by Soviet and later by U.S. spacecraft (see *Discovery 8-1*), no major maria were found there. The lunar far side (Figure 8.6) is composed almost entirely of highlands. This fact has great bearing on our theory of how the Moon's surface terrain came into being, for it implies that the processes involved could *not* have been entirely internal in nature. Earth's presence must somehow have played a role.

CONCEPT CHECK

✔ Describe three important ways in which the lunar maria differ from the highlands.

The Surface of Mercury

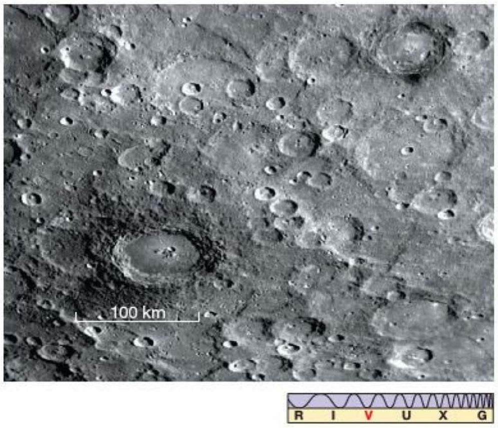
Mercury is difficult to observe from Earth because of Mercury's closeness to the Sun. Even with a fairly large telescope, we see it only as a slightly pinkish disk. Figure 8.7 is one of the few photographs of Mercury taken from Earth that shows any evidence of surface markings. Astronomers could only speculate about the faint, dark markings in the days before *Mariner 10*'s arrival. We now know that these markings are much like those seen by an observer gazing casually at Earth's Moon. The largest ground-based telescopes can resolve surface features on Mercury about as well as we can perceive features on the Moon with our unaided eyes.

In 1974, *Mariner 10* approached within 10,000 km of the surface of Mercury, sending back thousands of images that revolutionized our knowledge of the planet. ∞ (Sec. 6.6) Almost 35 years later, thanks to the *Messenger* mission, we now have even better, high-resolution images of this alien world. Figure 8.8 is a global view of the planet as we know it today, and Figure 8.9 shows a close-up of Mercury's surface that demonstrates striking similarities to our Moon. There are no signs of clouds, rivers, dust storms, or other aspects of weather. Much of Mercury's cratered surface bears a strong resemblance to the Moon's highlands. The crater walls are generally not as high as on the Moon, the craters are not as deep, and the ejected material landed closer to its impact sites, as expected given Mercury's

▲ FIGURE 8.7 **Mercury** Photograph of Mercury taken from Earth with a large ground-based optical telescope. Only a few faint surface features are discernible. *(Palomar Observatory/Caltech)*

◀ FIGURE 8.8 **Mercury, Up Close** Mercury is imaged here as a mosaic of photographs—a composite image constructed from many individual images—taken by the *Messenger* spacecraft in 2008 as it bypassed the planet. Notice the young, extensively rayed craters, here imaged with a resolution of about 5 km. *(NASA)*

greater surface gravity (which is a little more than twice that of the Moon). Mercury, however, shows no extensive lava flow regions akin to the lunar maria. Much of the discussion here and later in this chapter (see Sections 8.5 and 8.6) about the surface of Earth's Moon applies equally well to Mercury.



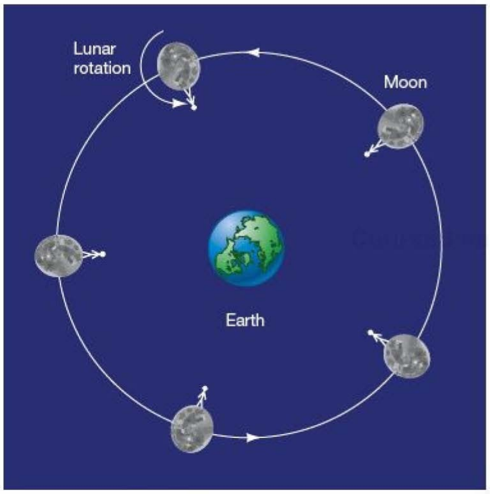
▲ FIGURE 8.9 **Mercury, Very Close** Another photograph of Mercury by *Messenger,* this one taken at much higher resolution (about 300 m). The dark material around the crater at lower left exemplifies how many of the large craters on Mercury tend to have dark halos about them. The reason is not yet understood. *(NASA)*

8.4 Rotation Rates

The spins of both the Moon and Mercury are strongly influenced by their proximity to their parent bodies—Earth and the Sun, respectively. By studying the processes responsible for the rotation rates observed today, astronomers learn about the role of tidal forces in shaping the details of the solar system.

The Rotation of the Moon

As mentioned earlier, the Moon's rotation period is precisely equal to its period of revolution about Earth—27.3 days—so the Moon keeps the same side facing Earth at all times (see Figure 8.10). To an astronaut standing on the Moon's near-side surface, Earth would appear almost stationary in the sky (although our planet's daily rotation would be clearly evident). This condition, in which the spin of one body is precisely equal to (or *synchronized* with) its revolution around another body, is known as a **synchronous orbit**.



Interactive FIGURE 8.10 **The Moon's Synchronous Rotation** As the Moon orbits Earth, it keeps one face permanently pointed toward our planet. To the astronaut shown here, Earth is always directly overhead. In fact, the Moon is slightly elongated in shape owing to Earth's tidal pull on it, with its long axis perpetually pointing toward Earth. (The elongation is highly exaggerated in this diagram.) It is often useful to think of the Earth and the Moon as a single system.

DISCOVERY 8-1

Lunar Exploration

The Space Age began in earnest on October 4, 1957, with the launch of the Soviet satellite *Sputnik 1.* Thirteen months later, on January 4, 1959, the Soviet *Luna 1,* the first human-made craft to escape Earth's gravity, passed the Moon. *Luna 2* crash-landed on the surface in September of that year, and *Luna 3* returned the first pictures of the far side a month later. The long-running *Luna* series established a clear Soviet lead in the early "space race" and returned volumes of detailed information about the Moon's surface. Several of the *Luna* missions landed and returned surface material to Earth.

The U.S. lunar exploration program got off to a rocky start. The first six attempts in the *Ranger* series, between 1961 and 1964, failed to accomplish their objective of just hitting the Moon. The last three were successful, however. *Ranger 7* collided with the lunar surface (as intended) on June 28, 1964. Five U.S. *Lunar Orbiter* spacecraft, launched in 1966 and 1967, were successfully placed in orbit around the Moon, and they relayed high-resolution images of much of the lunar surface back to Earth. Between 1966 and 1968, seven *Surveyor* missions soft-landed on the Moon and performed detailed analyses of the surface.

Many of these unmanned U.S. missions were performed in support of the manned *Apollo* program. On May 25, 1961, at a time when the U.S. space program was in great disarray, President John F. Kennedy declared that the United States would "send a man to the Moon and return him safely to Earth" before the end of the decade, and the *Apollo* program was born. On July 20, 1969, less than 12 years after *Sputnik* and only 8 years after the statement of the program's goal, *Apollo 11* commander Neil Armstrong became the first human to set foot on the Moon, in Mare Tranquilitatis (the Sea of Tranquility). Three-and-a-half years later, on December 14, 1972, scientist–astronaut Harrison Schmitt, of *Apollo 17,* was the last.

The astronauts who traveled in pairs to the lunar surface in each lunar lander (shown in the first photograph) performed numerous geological and other scientific studies on the surface. The later landers brought with them a "lunar rover"—a small golf cart–sized vehicle that greatly expanded the area the astronauts could cover. Probably the most important single aspect of the *Apollo* program was the collection of samples of surface rock from various locations on the Moon. In all, some 382 kg of material was returned to Earth. Chemical analysis and radioactive dating of these samples revolutionized our understanding of the Moon's surface history. No amount of Earth-based observations could have achieved the same results.

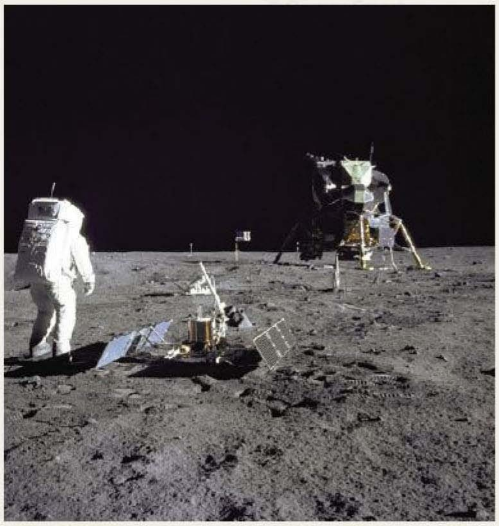
Each *Apollo* lander left behind a nuclear-powered package of scientific instruments called the *Apollo Lunar Surface Experiments Package* (*ALSEP,* second photograph) to monitor the solar wind, measure heat flow in the Moon's interior, and, perhaps most important, record lunar seismic activity. With several *ALSEPs* on the surface, scientists could determine the location of "moonquakes" by triangulation and map the Moon's inner

MA ANIMATION/VIDEO *Ranger* Spacecraft Descent to Moon

The fact that the Moon is in a synchronous orbit around Earth is no accident. It is an inevitable consequence of the gravitational interaction between those two bodies. Just as the Moon raises tides on Earth, Earth also produces a tidal bulge in the Moon. Indeed, because Earth is so much more massive, the tidal force on the Moon is about 20 times greater than that on Earth, and the Moon's tidal bulge is correspondingly larger.

In Chapter 7, we saw how lunar tidal forces are causing Earth's spin to slow and how, as a result, Earth will eventually rotate on its axis at the same rate as the Moon revolves around Earth. ∞ (Sec. 7.6) Earth's rotation will not become synchronous with the Earth–Moon orbital period for hundreds of billions of years. In the case of the Moon, however, the process has already gone to completion. The Moon's much larger tidal deformation caused it to evolve into a synchronous orbit long ago, and the Moon is said to have become ***tidally locked*** to Earth. Most of the moons in the solar system are similarly locked by the tidal fields of their parent planets.

Actually, the size of the lunar bulge is too great to be produced by Earth's present-day tidal influence. The explanation seems to be that, long ago, the distance from Earth to the Moon may have been as little as two-thirds of its current value, or about 250,000 km. Earth's tidal force on the Moon would then have been more than three times greater than it is today and could have accounted for the Moon's elongated shape. The resulting distortion could have "set" when the Moon solidified,



structure, obtaining information critical to our understanding of the Moon's evolution.

By any standards, the *Apollo* program was a spectacular success. It represents a towering achievement of the human race. The project's goals were met on schedule and within budget, and our knowledge of the Moon, Earth, and the solar system increased enormously. But the "Age of *Apollo*" was short lived. Public interest quickly waned. Over half a billion people breathlessly watched on television as Neil Armstrong set foot on the Moon, yet barely 3 years later, when the program was abruptly canceled for largely political (rather than scientific, technological, or economic) reasons, the landings had become so routine that they no longer excited the interest of the American public. Unmanned space science moved away from the Moon and toward the other planets, and the manned space program foundered. Perhaps one of the most amazing—and saddest— aspects of the *Apollo* program is that only now, some three decades later, is the U.S. (and perhaps also China) gearing up for new crewed missions to the Moon in the coming decade, reinventing lost expertise to do so.

In 1994, the small U.S. military satellite *Clementine* was placed in lunar orbit, to perform a detailed survey of the lunar surface. In 1998, NASA returned to the Moon for the first time in a quarter century with the launch of *Lunar Prospector,* another small satellite on a 1-year mission to study the Moon's structure and origins. Both missions were successful and amply demonstrated the wealth of information that can be obtained by low-budget spacecraft. In 2009, the *Lunar Reconnaissance Orbiter* spacecraft was inserted into a polar orbit just 50 km above the Moon's surface. *LRO*'s 1-year mission was to collect detailed information on the lunar surface, with particular emphasis on the polar regions, where water has been detected in permanently shadowed craters (see Section 8.5). The data returned by the mission will be critical in planning future human missions to the Moon.

Plans exist to establish permanent human colonies on the Moon, both for commercial ventures, such as mining, and for scientific research. The confirmation of water on the lunar surface may alleviate at least one major logistical problem associated with such an undertaking. In 2006 NASA announced a new program to reestablish its lunar exploration program, now in concert with a possible manned mission to Mars. This program may also include the construction of large optical, radio, and other telescopes on the lunar surface. Such instruments could be built larger than Earth-based devices and would benefit from perfect seeing and no light pollution.

Many astronomers are skeptical, arguing that the enormous cost of such facilities would outweigh the benefits they might offer compared to Earth-based and orbiting observatories. Others argue that the boost to space science from such a high-profile undertaking would easily justify the cost and that the existence of a suite of permanent, multiwavelength lunar observatories would be of enormous benefit to the field. At present, it remains to be seen whether the political will and economic resources exist to make this dream a reality.

ANIMATION/VIDEO First Step on the Moon

thus surviving to the present day, and at the same time accelerating the synchronization of the Moon's orbit.

Measurement of Mercury's Spin

In principle, the ability to discern surface features on Mercury should allow us to measure its rotation rate simply by watching the motion of a particular region around the planet. In the mid-19th century, an Italian astronomer named Giovanni Schiaparelli did just that. He concluded that Mercury always keeps one side facing the Sun, much as our Moon perpetually presents only one face to Earth. The explanation suggested for this supposed synchronous rotation was the same as that for the Moon: The tidal bulge raised in Mercury by the Sun had modified the planet's rotation rate until the bulge always pointed directly at the Sun. Although the surface features could not be seen clearly, the combination of Schiaparelli's observations and a plausible physical explanation was enough to convince most astronomers, and the belief that Mercury rotates synchronously with its revolution about the Sun (i.e., once every 88 Earth days) persisted for almost half a century.

In 1965, astronomers making observations of Mercury from the Arecibo radio telescope in Puerto Rico (see Figure 5.21) discovered that this long-held view was in error. They used the Arecibo instrument as a giant radar gun, sending out pulses of radio waves toward the planet and waiting for the echoes to

MORE PRECISELY 8-1

Why Air Sticks Around

Why do some planets and moons have atmospheres, while others do not, and what determines the composition of the atmosphere if one exists? Why does a layer of air, made up mostly of nitrogen and oxygen, lie just above Earth's surface? After all, experience shows that most gas naturally expands to fill all the volume available. Perfume in a room, fumes from a poorly running engine, and steam from a teakettle all disperse rapidly until we can hardly sense them. Why doesn't our planet's atmosphere similarly disperse by floating away into space?

The answer is that *gravity* holds it down. Earth's gravitational field exerts a pull on all the atoms and molecules in our atmosphere, preventing them from escaping. However, gravity is not the only influence acting, for if it were, all of Earth's air would have fallen to the surface long ago. *Heat*—the rapid random motion of the molecules in a gas—competes with gravity to keep the atmosphere buoyant. Let's explore this competition between gravity and heat in a little more detail.

All gas molecules are in constant random motion. The temperature of any gas is a direct measure of this motion: The hotter the gas, the faster the molecules are moving. ∞ *(More Precisely 3-1)* The Sun continuously supplies heat to our planet's atmosphere, and the resulting rapid movement of heated molecules produces *pressure*, which tends to oppose the force of gravity, preventing our atmosphere from collapsing under its own weight.

An important measure of the strength of a body's gravity is the body's *escape speed*—the speed needed for any object to escape forever from its surface. ∞ (Sec. 2.8) This speed increases with increased mass or decreased radius of the parent body (often a moon or a planet). In convenient (Earth) units, it can be expressed as

$$\text{escape speed (in km/s)} = 11.2\sqrt{\frac{\text{mass of body (in Earth masses)}}{\text{radius of body (in Earth radii)}}}.$$

Thus, Earth's escape speed is $11.2\sqrt{1/1} = 11.2$ km/s. If the *mass* of the parent body is quadrupled, the escape speed doubles. If the parent body's *radius* quadruples, then the escape speed is halved. In other words, you need high speed to escape the gravitational attraction of a very massive or very small body, but you can escape from a less massive or larger body at lower speeds.

To determine whether a planet will retain an atmosphere, we must compare the planet's escape speed with the *molecular speed*, which is the average speed of the gas particles making up the planet's atmosphere. This speed actually depends not only on the temperature of the gas, but also on the mass of the individual molecules—the hotter the gas or the smaller the molecular mass, the higher is the average speed of the molecules:

$$\text{average molecular speed (in km/s)} = 0.157\sqrt{\frac{\text{gas temperature }(K)}{\text{molecular mass (hydrogen atom masses)}}}.$$

Thus, increasing the absolute temperature of a sample of gas by a factor of four—for example, from 100 K to 400 K—doubles the average speed of its constituent molecules, and, at a given temperature, molecules of hydrogen (H_2: molecular mass = 2) in air move, on average, four times faster than molecules of oxygen (O_2: molecular mass = 32), which are 16 times heavier.

EXAMPLE 1 For nitrogen (N_2: molecular mass = 28) and oxygen (O_2: molecular mass = 32) in Earth's atmosphere, where the temperature near the surface is nearly 300 K, the preceding formula yields the following average molecular speeds:

$$\text{nitrogen:}\quad 0.157\text{ km/s} \times \sqrt{\frac{300}{28}} = 0.51\text{ km/s};$$

$$\text{oxygen:}\quad 0.157\text{ km/s} \times \sqrt{\frac{300}{32}} = 0.48\text{ km/s}.$$

These speeds are far smaller than the 11.2 km/s needed for a molecule to escape into space. As a result, Earth is able to retain its nitrogen–oxygen atmosphere. On the whole, *our planet's gravity simply has more influence than the heat of our atmosphere.*

return. (See Figure 2.18 for a similar measurement of the planet Venus.) ∞ (Sec. 2.6) The returning pulses were much weaker than the original outgoing beam, but the huge size of the Arecibo dish allowed the researchers to detect the reflected signal and then analyze it to determine Mercury's rotation rate.

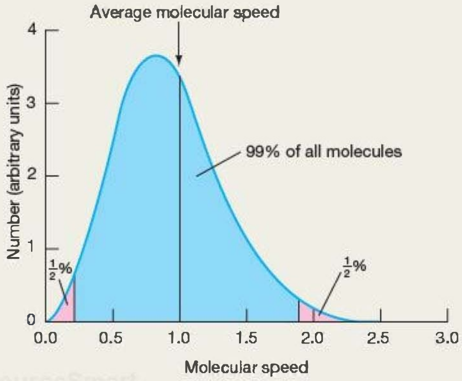
To illustrate the basic method, Figure 8.11 shows a radar pulse reflecting from the surface of a hypothetical planet. The reflected signal as a whole may be redshifted or blueshifted by the Doppler effect, depending on the overall radial velocity of the planet relative to Earth. ∞ (Sec. 3.5) But in addition, if the planet is rotating, the radiation reflected from the side moving toward us returns at a slightly higher frequency than the radiation reflected from the receding side. (Think of the two hemispheres as being separate sources of radiation moving at slightly different velocities, one toward us and one away.) The effect is very similar to the rotational line broadening discussed in Chapter 4, except that in this case the radiation is not emitted by the planet, but only reflected from its surface. ∞ (Sec. 4.5) Thus, even if the original beam consists of radiation of a single frequency, the reflected signal contains a spread of frequencies on either side of the original. By measuring that spread we can determine the planet's rotational speed.

In this way, the Arecibo researchers found that the rotation period of Mercury is not 88 days, as had previously been thought, but 59 days, exactly two-thirds of the planet's orbital period. Because there are exactly three rotations for every two revolutions, we say that there is a 3:2 *spin–orbit resonance*

In reality, the situation is a little more complicated than a simple comparison of speeds. Atmospheric molecules can gain or lose speed by bumping into one another or by colliding with objects near the ground. Thus, although we can characterize a gas by its average molecular speed, the molecules do not *all* move at the same speed, as illustrated in the accompanying figure. A tiny fraction of the molecules in any gas have speeds much greater than average—one molecule in two million has a speed more than three times the average, and one in 10^{16} exceeds the average by more than a factor of five. This means that at any instant, *some* molecules are moving fast enough to escape, even when the average molecular speed is much less than the escape speed. The result is that all planetary atmospheres slowly leak away into space.

Don't be alarmed—the leakage is usually very gradual! As a rule of thumb, if the escape speed from a planet exceeds the average speed of a given type of molecule by a factor of six or more, then molecules of that type will not have escaped from the planet's atmosphere in significant quantities in the 4.6 billion years since the solar system formed. Conversely, if the escape speed is less than six times the average speed of molecules of a given type, then most of them will have escaped by now, and we should not expect to find them in the atmosphere.

Interactive



For air on Earth, the mean molecular speeds of oxygen and nitrogen that we just computed are comfortably below one-sixth of the escape speed. However, if the Moon originally had an Earth-like atmosphere, that lunar atmosphere would have been heated by the Sun to much the same temperature as Earth's air today, so the average molecular speed would have been about 0.5 km/s. Because the Moon's escape speed is only $11.2\sqrt{0.012/0.27} = 2.4$ km/s—less than six times the average molecular speed—any original lunar atmosphere long ago dispersed into interplanetary space. Mercury's escape speed is $11.2\sqrt{0.055/0.38} = 4.2$ km/s However, its peak surface temperature is around 700 K, corresponding to an average molecular speed for nitrogen or oxygen of about 0.8 km/s, more than one-sixth of the escape speed, so there has been ample time for those gases to escape.

EXAMPLE 2 We can use the foregoing arguments to understand some aspects of atmospheric *composition.* Hydrogen molecules (H_2: molecular mass = 2) move, on average, at about 1.9 km/s in Earth's atmosphere at sea level, so they have had time to escape since our planet formed (6×1.9 km/s = 11.4 km/s, which is greater than Earth's 11.2-km/s escape speed). Consequently, we find very little hydrogen in Earth's atmosphere today. However, on the planet Jupiter, with a lower temperature (about 100 K), the speed of hydrogen molecules is correspondingly slower—about 1.1 km/s. At the same time, Jupiter's escape speed is 60 km/s, over five times higher than Earth's. For those reasons, Jupiter has retained its hydrogen—in fact, hydrogen is the dominant ingredient of Jupiter's atmosphere.

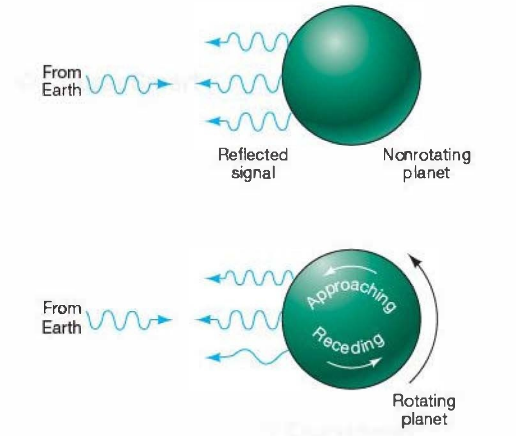
in Mercury's motion. In this context, the term resonance just means that two characteristic times—here, Mercury's day and year—are related to each other in a simple way. An even simpler example of a spin–orbit resonance is the Moon's orbit around Earth. In that case, the rotation is synchronous with the revolution, and the resonance is said to be 1:1.

Figure 8.12 illustrates some implications of Mercury's curious rotation for a hypothetical inhabitant of the planet. Mercury's solar day—the time from noon to noon, say—is 2 Mercury years long! The Sun stays "up" in the black Mercury sky for almost 3 Earth months at a time, after which follow nearly 3 Earth months of darkness. At any given point in its orbit, Mercury presents the same face to the Sun, not every time it revolves, but *every other* time.

Explanation of Mercury's Rotation

Mercury's 3:2 spin–orbit resonance did not occur by chance. What mechanism establishes and maintains it? In the case of the Moon orbiting Earth, the 1:1 resonance is the result of tidal forces. In essence, the lunar rotation period, which probably started off much shorter than its present value, has lengthened so that the tidal bulge created by Earth is fixed relative to the body of the Moon. Tidal forces (this time due to the Sun) are also responsible for Mercury's 3:2 resonance, but in a much more subtle way.

Mercury cannot settle into a 1:1 resonance because its orbit around the Sun is quite eccentric. By Kepler's second law, Mercury's orbital speed is greatest at perihelion (closest



▲ FIGURE 8.11 **Planetary Radar** A radar beam (blue waves) reflected from a rotating planet yields information about both the planet's line-of-sight motion and its rotation rate.

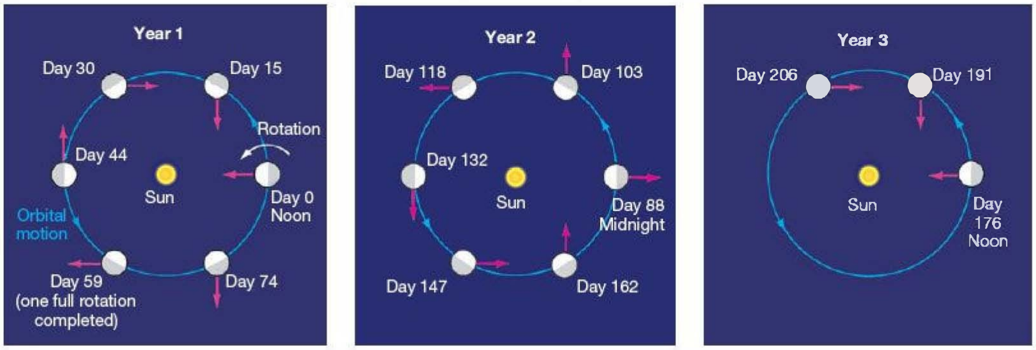
approach to the Sun) and least at aphelion (greatest distance from the Sun). ∞ *(More Precisely 2-1)* A moment's thought shows that, because of these variations in the planet's orbital speed, there is no way that the planet (rotating at a constant rate) can remain in a synchronous orbit. If its rotation were synchronous near perihelion, it would be too rapid at aphelion, and synchronism at aphelion would produce too slow a rotation at perihelion.

Tidal forces always act so as to synchronize the rotation rate with the instantaneous orbital speed, but such synchronization cannot be maintained over Mercury's entire orbit. What happens? The answer is found when we realize that tidal effects diminish very rapidly with increasing distance. The tidal forces acting on Mercury at perihelion are much greater than those at aphelion, so perihelion "won" the struggle to determine the rotation rate. In the 3:2 resonance, Mercury's orbital and rotational motion are almost exactly synchronous *at perihelion*, so that particular rotation rate was naturally "picked out" by the Sun's tidal influence on the planet. Notice that even though Mercury rotates through only 180° between one perihelion and the next (see Figure 8.12), the appearance of the tidal bulge is the *same* each time around.

Resonances such as these occur quite frequently in the solar system. Many additional examples can be found in the motion of the planets, their moons and rings, as well as in orbits of many asteroids and Kuiper belt objects. The rotation of Mercury is one of the simplest nonsynchronous resonances known. Many resonances are much more complex. These intricate interactions are responsible for much of the fine detail observed in the motion of our planetary system.

The Sun's tidal influence also causes Mercury's rotation axis to be exactly perpendicular to its orbital plane. As a result, and because of Mercury's eccentric orbit and the spin–orbit resonance, some points on the surface get much hotter than others. In particular, the two (diametrically opposite) points on the equator where the Sun is directly overhead at perihelion get hottest of all. They are called the *hot longitudes*. The peak temperature of 700 K mentioned earlier occurs at noon at those two locations. At the *warm longitudes*, where the Sun is directly overhead at aphelion, the peak temperature is about 150 K cooler—a mere 550 K.

By contrast, the Sun is always on the horizon as seen from the planet's poles, so temperatures there never reach



Interactive FIGURE 8.12 **Mercury's Rotation** Mercury's orbital and rotational motions combine to produce a day that is 2 Mercury years long. The red arrow represents an observer standing on the surface of the planet. At day 0 (center right in Year 1 drawing), it is noon for our observer and the Sun is directly overhead. By the time Mercury has completed one full orbit around the Sun and moved from day 0 to day 88, it has rotated on its axis exactly 1.5 times, so that it is now midnight at the observer's location. After another complete orbit, it is noon once again on day 176 (center right in Year 3 drawing). The eccentricity of Mercury's orbit is not shown in this simplified diagram.

the sizzling levels of the equatorial regions. Earth-based radar studies carried out during the 1990s suggest that Mercury's polar temperatures may be as low as 125 K and that, despite the planet's scorched equator, the poles may be covered with extensive sheets of water ice. (See Section 8.5 for similar findings regarding the Moon.)

CONCEPT CHECK

✔ How has gravity influenced the rotation rates of the Moon and Mercury?

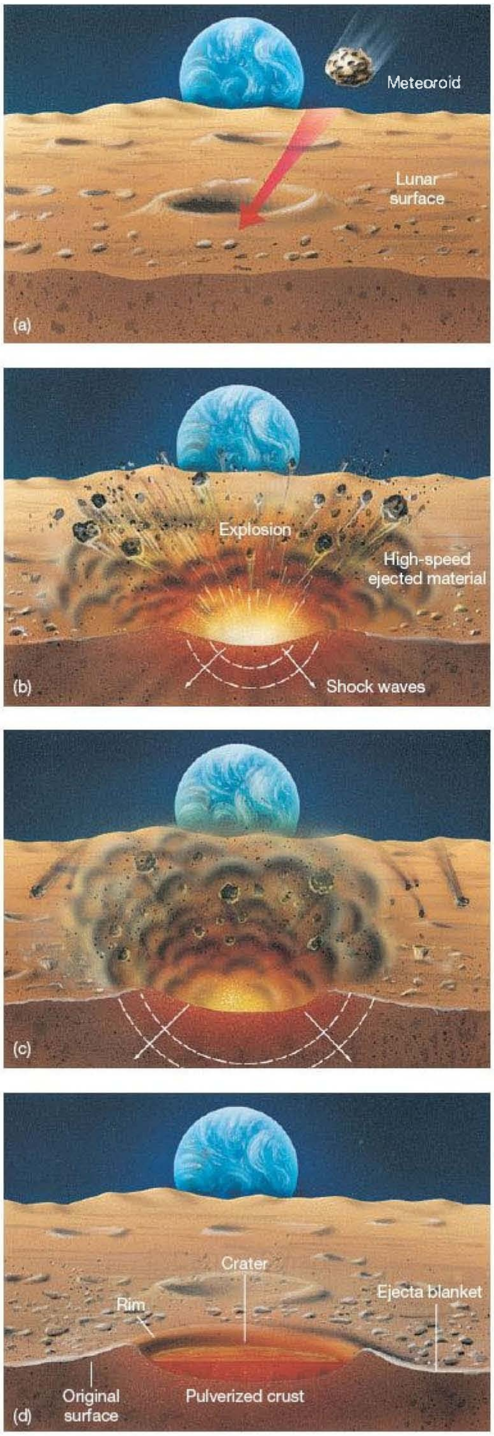
8.5 Lunar Cratering and Surface Composition

On Earth, the combined actions of wind and water erode our planet's surface and reshape its appearance almost daily. Coupled with the never-ending motion of Earth's surface plates, the result is that most of the ancient history of our planet's surface is lost to us. The Moon, in contrast, has no air, no water, no plate tectonics, and no ongoing volcanic or seismic activity. Consequently, features dating back almost to its formation are still visible today.

Meteoritic Impacts

The primary agent of change on the lunar surface is interplanetary debris, in the form of *meteoroids*. This material, much of it rocky or metallic in composition, is strewn throughout the solar system, orbiting the Sun in interplanetary space, perhaps for billions of years, until it happens to collide with some planet or moon. ∞ (Sec. 6.5) On Earth, most meteoroids burn up in the atmosphere, producing the streaks of light known as *meteors*, or "shooting stars." But the Moon, without an atmosphere, has no protection against this onslaught. Large and small meteoroids zoom in and collide with the surface, sometimes producing huge craters. Over billions of years, these collisions have scarred, cratered, and sculpted the lunar landscape. Craters are still being formed today—even as you read this—all across the surface of the Moon.

Meteoroids generally strike the Moon at speeds of several kilometers per second. At these speeds, even a small piece of matter carries an enormous amount of energy. For example, a 1-kg object hitting the Moon's surface at 10 km/s releases as much energy as the detonation of 10 kg of TNT! As illustrated in Figure 8.13, the impact of a meteoroid with



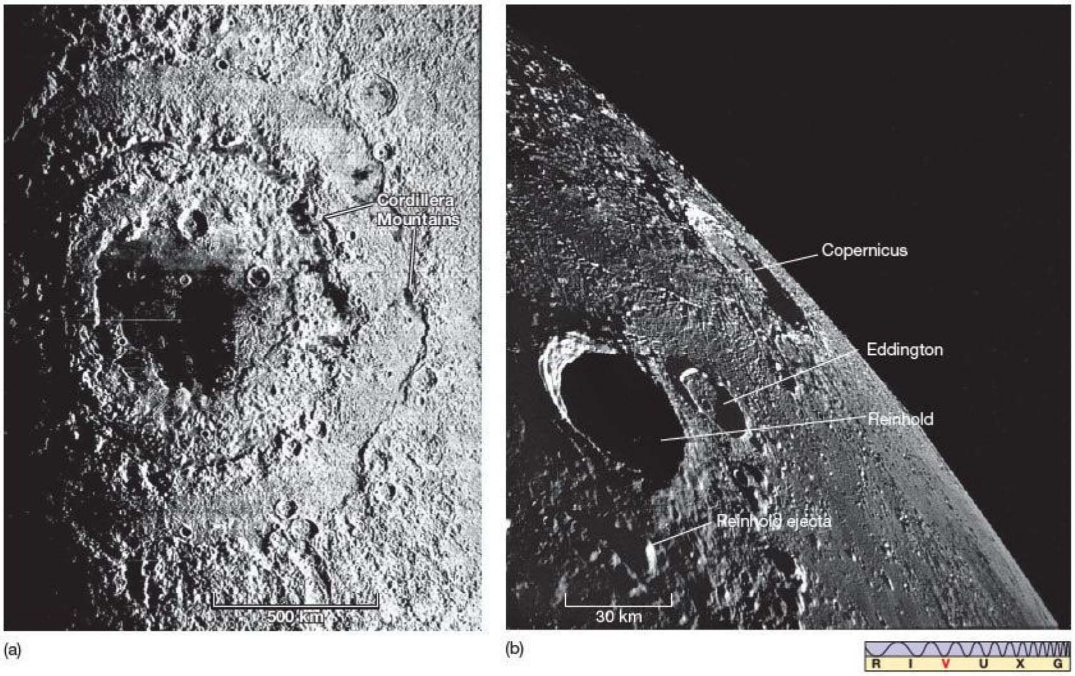
Interactive FIGURE 8.13 Meteoroid Impact Several stages in the formation of a crater by meteoritic impact. (a) A meteoroid strikes the surface, releasing a large amount of energy. (b, c) The resulting explosion ejects material from the impact site and sends shock waves through the underlying surface. (d) Eventually, a characteristic crater surrounded by a blanket of ejected material results. Planets and moons are not isolated in space; rather they are often hit by debris in their larger environments.

the surface causes sudden and tremendous pressures to build up, heating the normally brittle rock and deforming the ground like heated plastic. The ensuing explosion pushes previously flat layers of rock up and out, forming a crater.

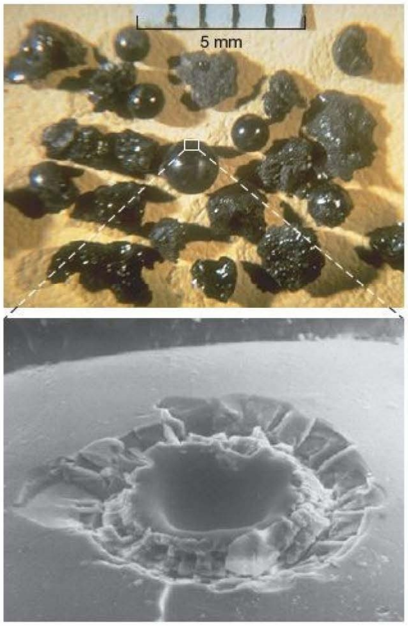
The diameter of the eventual crater is typically 10 times that of the incoming meteoroid; the depth of the crater is about twice the meteoroid's diameter. Thus, our 1-kg meteoroid, measuring perhaps 10 cm across, would produce a crater about 1 m in diameter and 20 cm deep. Shock waves from the impact pulverize the lunar surface to a depth many times that of the crater itself. Numerous rock samples brought back by the *Apollo* astronauts show patterns of repeated shattering and melting---direct evidence of the violent shock waves and high temperatures produced in meteoritic impacts. The material thrown out by the explosion surrounds the crater in a layer called an *ejecta blanket.* The ejected debris ranges in size from fine dust to large boulders. Figure 8.14(a) shows the result of one particularly large meteoritic impact on the Moon. As shown in Figure 8.14(b), the larger pieces of ejecta may themselves form secondary craters.

In addition to the bombardment by meteoroids with masses of a gram or more, a steady "rain" of *micrometeoroids* (debris with masses ranging from a few micrograms up to about 1 gram) also eats away at the structure of the lunar surface. Some examples can be seen in Figure 8.15, a photomicrograph (a photograph taken through a microscope) of some glassy "beads" brought back to Earth by *Apollo* astronauts. The beads themselves were formed during the explosion following the impact of a meteoroid, when surface rock was melted, ejected, and rapidly cooled. Note how several of the beads also display fresh miniature craters caused by micrometeoroids that struck the beads after they had cooled and solidified.

In fact, the *rate* of cratering decreases rapidly with the size of the crater—fresh large craters are scarce, but small craters are common. The reason for this is simple: There just aren't very many large chunks of debris in interplanetary



▲ **FIGURE 8.14** **Large Lunar Craters** (a) A large lunar crater, called the Orientale Basin. The meteorite that produced this crater thrust up much surrounding matter, which can be seen as concentric rings of cliffs called the Cordillera Mountains. The outermost ring is nearly 1000 km in diameter. Notice the smaller, sharper, younger craters that have impacted this ancient basin in more recent times. (b) Two smaller craters called Reinhold and Eddington sit amid the secondary cratering resulting from the impact that created the 90-km-wide Copernicus crater (near the horizon) about a billion years ago. The ejecta blanket from crater Reinhold, 40 km across and in the foreground, can be seen clearly. The view was obtained by looking northeast from the lunar module during the *Apollo 12* mission. *(NASA)*



▲ **FIGURE 8.15 Microcraters** Craters of all sizes litter the lunar landscape. Some shown here, embedded in glassy beads retrieved by *Apollo* astronauts, measure only 0.01 mm across. (The scale at the top is in millimeters.) The beads themselves were formed during the explosion following a meteoroid impact, when surface rock was melted, ejected, and rapidly cooled. *(NASA)*

space, so their collisions with the Moon are rare. At present average rates, one new 10-km (diameter) lunar crater is formed roughly every 10 million years, a new meter-sized crater is created about once a month, and centimeter-sized craters are formed every few minutes.

Cratering History of the Moon

Astronomers can use the known ages (from radioactive dating) of Moon rocks to estimate the rate of cratering in the past. One very important result of this work is the discovery that the Moon was subjected to an extended period of intense meteoritic bombardment roughly 4 billion years ago. Indeed, this is a key piece of evidence supporting the condensation theory of solar system formation. ∞ (Sec. 6.7)

As we have seen, the heavily cratered highlands are older than the less-cratered maria, but the difference in cratering is not simply a matter of exposure time. Astronomers now think that the Moon, and presumably the entire inner solar system, experienced a sudden drop in meteoritic bombardment about 3.9 billion years ago. The highlands solidified and received most of their craters before that time, whereas the maria solidified afterward. The rate of cratering has remained relatively low ever since.

The great basins that comprise the maria are thought to have been created during the final stages of the heavy bombardment, between about 4.1 and 3.9 billion years ago. Subsequent volcanic activity filled the craters with lava, ultimately creating the formations we see today as the lava turned into solid rock. In a sense, then, the maria *are* oceans—ancient seas of molten lava, now solidified.

Not all these great craters became flooded with lava, however. One of the youngest craters is the Orientale Basin (Figure 8.14a), which formed about 3.9 billion years ago. This crater did not undergo much subsequent volcanism, and we can recognize its structure as an impact crater rather than as another mare. Similar "unflooded" basins are seen on the lunar far side (Figure 8.6).

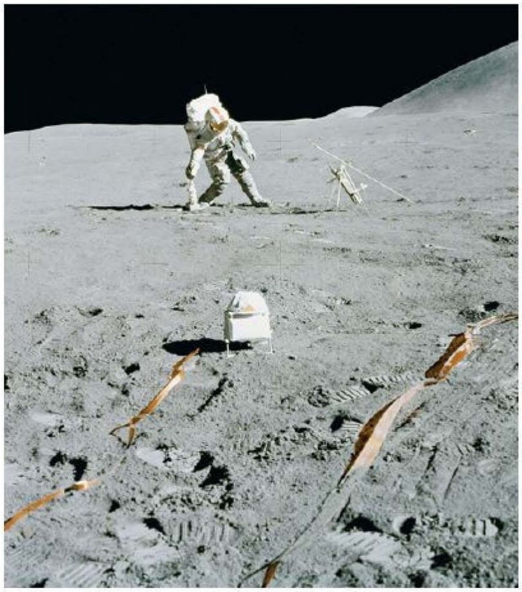
Apart from meteorites found on Earth, the Moon is the only solar system object for which we have accurate age measurements, from radioactive dating of samples returned to Earth. However, studies of lunar cratering provide astronomers with an important alternative means of estimating ages in the solar system. By counting craters on a planet, moon, or asteroid and using the Moon to calibrate the numbers, an approximate age for the surface can be obtained. In fact, this is how most of the ages presented in the next few chapters are determined. Note that, as with radioactive dating, the technique measures only the time since the surface in question last solidified—all cratering is erased and the clock is reset if the rock melts. ∞ *(More Precisely 7-2)*

Lunar Dust

Meteoroid collisions with the Moon are the main cause of the layer of pulverized ejecta—also called lunar dust, or *regolith* (meaning "fine rocky layer")—that covers the lunar landscape to an average depth of about 20 m. This microscopic dust has a typical particle size of about 0.01 mm. In consistency, it is rather like talcum powder or ready-mix dry mortar. Figure 8.16 shows an *Apollo* astronaut's boot prints in the regolith, which is thinnest on the maria (10 m) and thickest on the highlands (over 100 m deep in places).

The constant barrage from space results in a slow, but steady, erosion of the lunar surface. The soft edges of the craters visible in the foreground of Figure 8.17 are the result of this process. In the absence of erosion, those features would still be as jagged and angular today as they were just after they formed. Instead, the steady buildup of dust due to innumerable impacts has smoothed their outlines and will probably erase them completely in about 100 million years.

From the known dependence of the cratering rate on the size of a crater, planetary scientists can calculate how many small craters they would expect to find, given the numbers of large craters actually observed. When they make this calculation, they find a shortage of craters less than



▲ FIGURE 8.16 **Regolith** The lunar soil, or regolith, is a layer of powdery dust covering the lunar surface to a depth of roughly 20 m. Note the bootprints in the foreground of the *Apollo* astronaut, seen here adjusting some instruments for testing the composition of soil near Mount Hadley. The astronaut's weight has compacted the regolith to a depth of a few centimeters. Even so, these boot prints will probably survive for more than a million years. *(NASA)*

▲ FIGURE 8.17 **Lunar Surface** The lunar surface is not entirely changeless. Despite the complete lack of wind and water on the airless Moon, the surface has still eroded a little under the constant "rain" of meteoroids, especially micrometeoroids. Note the soft edges of the craters visible in the foreground of this image. In the absence of erosion, these features would be as jagged and angular today as they were when they formed. (The twin tracks were made by the *Apollo* lunar rover.) *(NASA)*

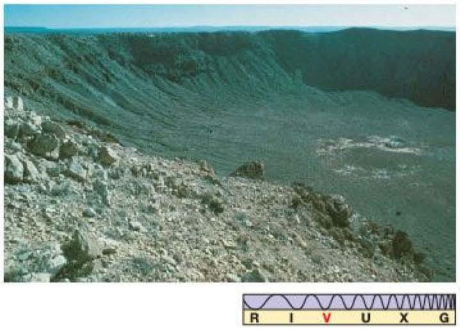
about 20 m deep. These "missing" craters have been filled in by erosion over the lifetime of the Moon. This gives us a very rough estimate of the average erosion rate: about 5 m per billion years, or roughly 1/10,000 the rate on Earth.

The current lunar erosion rate is very low because meteoritic bombardment on the Moon is a much less effective erosive agent than are wind and water on Earth. For comparison, the Barringer Meteor Crater (Figure 8.18) in the Arizona desert, one of the largest meteoroid craters on Earth, is only 25,000 years old, but has already undergone noticeable erosion. It will probably disappear completely in just a few million years, quite a short time geologically. If a crater that size had formed on the Moon even 4 billion years ago, it would still be plainly visible today. Even the shallow boot prints shown in Figure 8.16 are likely to remain intact for several million years.

Lunar Ice?

In contrast to Earth's soil, the lunar regolith contains no organic matter like that produced by biological organisms. No life whatsoever exists on the Moon. Nor were any fossils found in *Apollo* samples. Lunar rocks are barren of life and apparently always have been. NASA was so confident of this fact that the astronauts were not even quarantined on their return from the last few *Apollo* landings. Furthermore, all the lunar samples returned by the U.S. and Soviet Moon programs were bone dry—they didn't even contain minerals having water molecules locked within their crystal structure. Terrestrial rocks, by contrast, are almost always 1 or 2 percent water. The main reasons for this lack of water are the Moon's lack of an atmosphere and the high (up to 400 K) daytime temperatures found over most of the lunar surface.

Some regions of the Moon *are* thought to contain water, however—in the form of ice. As early as the 1960s, some scientists had considered the theoretical possibility that ice might be found near the lunar poles. Since the Sun never rises more than a few degrees above the horizon, as seen from the Moon's polar regions, temperatures on the permanently shaded floors of craters near the poles never exceed about 100 K. Consequently, those scientists theorized, any water ice there could have remained permanently frozen



◀ **FIGURE 8.18 Barringer Crater** The Barringer Meteor Crater, near Winslow, Arizona, is 1.2 km in diameter and 0.2 km deep. (Note the access road at right for scale.) Geologists think that a large meteoroid whacked Earth and formed this crater about 25,000 years ago. The meteoroid was probably about 50 m across and likely weighed around 200,000 tons. The inset shows a closeup of one of the interior walls of the crater. *(U.S. Geological Survey)*

since the very early days of the solar system, never melting or vaporizing and hence never escaping into space.

In 1996, mission controllers of the *Clementine* mission (an experimental U.S. Defense Department spacecraft) reported that radar echoes captured from an old, deep crater near the lunar south pole suggested deposits of low-density material, probably water ice, at a depth of a few meters. In 1998, NASA's *Lunar Prospector* mission confirmed *Clementine*'s findings, reporting large amounts of ice—possibly totaling trillions of tons—at both lunar poles. At first, it appeared that the ice was mainly in the form of tiny crystals mixed with the lunar regolith, spread over many tens of thousands of square kilometers of deeply shadowed crater floors. However, later analysis of the data suggested that much of the ice might instead be in the form of smaller, but more concentrated "lakes" of nearly pure material lying just below the surface.

Given the potential importance of this finding, in an attempt to gain more information about possible lunar ice NASA scientists decided to end the *Lunar Prospector* mission in a spectacular way. As the spacecraft neared the end of its operational lifetime, it was directed to crash into one of the deep craters in which the ice was suspected to hide. The hope was that telescopes on Earth might detect spectroscopic signatures of water vapor released by the impact. No water vapor was seen, although mission planners knew that, due to the many uncertainties involved, the probability of success was low.

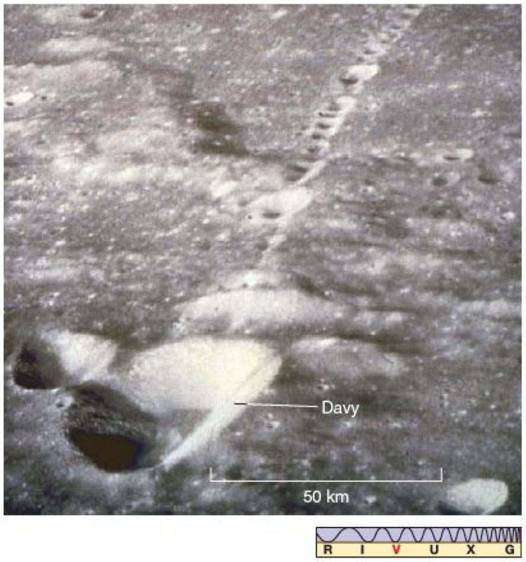
In late 2009, NASA tried again, on an even larger scale, with the *Lunar CRater Observation and Sensing Satellite* (*LCROSS*) mission, launched along with the *Lunar Reconnaissance Orbiter* mission (*LRO*; see *Discovery 8-1*). The Centaur rocket that boosted both missions into lunar orbit was crashed into another deeply shadowed crater near the lunar south pole, while *LCROSS* watched from a few thousand kilometers away, radioing its spectroscopic data back to Earth via *LRO* before it too impacted the Moon minutes later. Detectors on *HST* and on Earth failed to detect the anticipated plume of material from the impact, disappointing thousands of amateur (and professional) astronomers eagerly awaiting the spectacle.

However, a few weeks later NASA scientists announced that detailed analysis of the *LCROSS* data had indeed confirmed the presence of water molecules in the ejecta. The amount of water was not great—only about 1 part in 100,000, less than in the desert sand on Earth—but it was more than enough to corroborate the earlier reports.

Where did this ice come from? Most likely, it was brought to the lunar surface by meteoroids and comets. (We will see in Chapter 15 that this is the likely origin of Earth's water, too.) Any ice that survived the impact would have been scattered across the surface. Over most of the Moon, that ice would have rapidly vaporized and escaped, but in the deep basins near the poles, it survived and built up over time. Whatever its origin, the polar ice may be a crucial component of any serious attempt at human colonization of the Moon: The anticipated cost of transporting a kilogram of water from Earth to the Moon is between $2,000 and $20,000, prompting one lunar scientist to describe the lunar ice deposits as "possibly the most valuable piece of real estate in the solar system."

Lunar Volcanism

Only a few decades ago, debate raged in scientific circles about the origin of lunar craters, with most scientists of the opinion that the craters were the result of volcanic activity. We now know that almost all lunar craters are



▲ **FIGURE 8.19 Crater Chain** This "chain" of well-ordered craters was photographed by an *Apollo 14* astronaut. The largest crater, called Davy, is located on the western edge of Mare Nubium. The entire field of view measures about 100 km across. *(NASA)*

actually meteoritic in origin. However, a few apparently are not. Figure 8.19 shows an intriguing alignment of several craters in a *crater-chain* pattern so straight that it is highly unlikely to have been produced by the random collision of meteoroids with the surface. Instead, the chain probably marks the location of a subsurface fault—a place where cracking or shearing of the surface once allowed molten matter to well up from below. As the lava cooled, it formed a solid "dome" above each fissure. Subsequently, the underlying lava receded and the centers of the domes collapsed, forming the craters we see today. Similar features have been observed on Venus by the orbiting *Magellan* probe (see Chapter 9).

Many other examples of lunar volcanism are known, both in telescopic observations from Earth and in the close-up photographs taken during the *Apollo* missions. Figure 8.20 shows a volcanic rille, a ditch where molten lava once flowed. There is good evidence for surface volcanism early in the Moon's history, and volcanism explains the presence of the lava that formed the maria. However, whatever volcanic activity once existed on the Moon ended long ago. The measured ages for rock samples returned from the Moon are all greater than 3 billion years. (Recall from *More Precisely 7-2* that the radioactivity clock starts "ticking" when the rock solidifies.) Apparently, the maria solidified over 3 billion years ago, and the Moon has been dormant ever since.

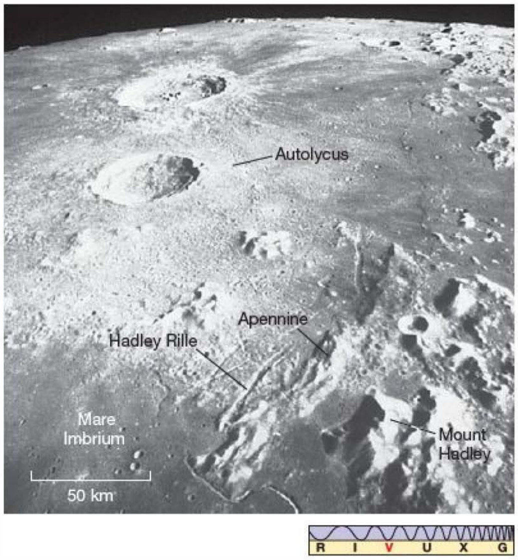
CONCEPT CHECK

✔ How has meteoritic bombardment affected the surface of the Moon?

8.6 The Surface of Mercury

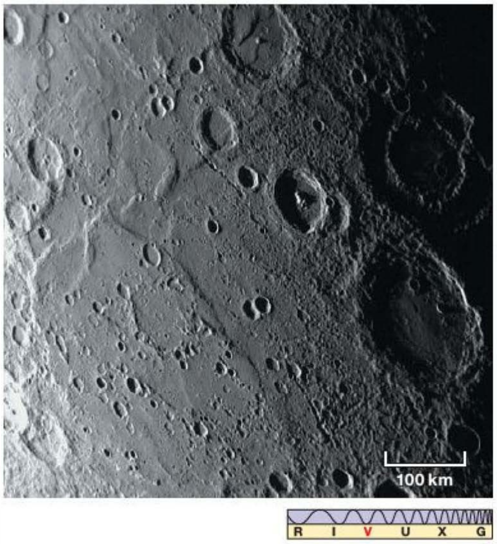
Like craters on the Moon, almost all craters on Mercury are the result of meteoritic bombardment. However, Mercury's craters are less densely packed than their lunar counterparts, and extensive **intercrater plains** cover some 40 percent of the planet's surface. The crater walls are generally not as high as those on the Moon, and the ejected material appears to have landed closer to the impact site exactly as we would expect on the basis of Mercury's stronger surface gravity.

Following *Mariner 10*'s visit, the leading explanation for Mercury's relative lack of craters was that the older craters were filled in by volcanic activity, in much the same way as

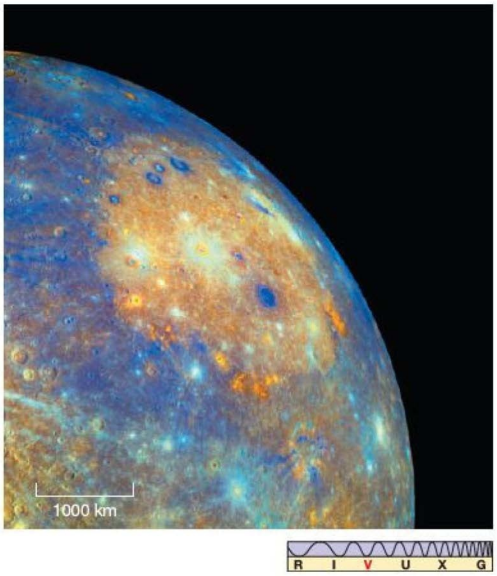


▲ **FIGURE 8.20 Lunar Volcanism** A volcanic rille, photographed from the *Apollo 15* spacecraft orbiting the Moon, can be seen clearly here (bottom and center) winding its way through one of the maria. Called Hadley Rille, this system of valleys runs along the base of the Apennine Mountains (lower right) at the edge of the Mare Imbrium (to the left). Autolycus, the large crater closest to the center, spans 40 km. The shadow-sided, most prominent peak at lower right, Mount Hadley, rises almost 5 km high. *(NASA)* the Moon's maria filled in older craters as they formed. More detailed observations by *Messenger* appear to confirm that conclusion, and many geologists think that much of Mercury's crust may have formed through repeated volcanic eruptions. Still, the intercrater plains do not look much like maria—they are much lighter in color and not as flat. Although the details of how Mercury's landscape came to look the way it does remain unexplained, the apparent absence of rilles or other obvious features associated with very large-scale lava flows, along with the light color of the lava-flooded regions, suggests that Mercury's volcanic past was different from the Moon's.

Mercury has at least one type of surface feature not found on the Moon. Figure 8.21 shows a **scarp,** or cliff, on the surface that does not appear to be the result of volcanic or any other familiar geological activity. The scarp cuts across several craters, which indicates that whatever produced it occurred *after* most of the meteoritic bombardment was over. Mercury shows no evidence of crustal motions like plate tectonics on Earth—no fault lines, spreading sites, or indications of plate collisions are seen. ∞ (Sec. 7.4) The scarps, of which several are known from the *Mariner* and *Messenger* images, probably formed when the planet's interior cooled and shrank long ago, much as wrinkles form on the skin of an old, shrunken apple. On the basis of the amount of cratering observed in the surrounding terrain (as discussed in the previous section), astronomers estimate that the scarps probably formed about 4 billion years ago.



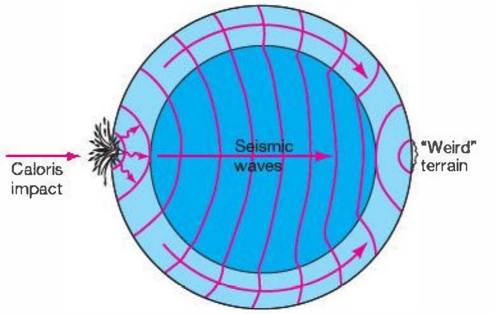
▲ FIGURE 8.21 **Mercury's Surface** Scarps, or ridges, on Mercury's surface, as photographed by *Messenger*. This cliff seems to have formed when the planet's crust cooled and shrank early in its history, causing a crease in the surface. Running diagonally across the center of the frame, the scarp is several hundred kilometers long and up to 3 km high in places. *(NASA)*



▲ FIGURE 8.22 **Mercury's Basin** Mercury's most prominent geological feature—the Caloris Basin—measures about 1400 km across and is ringed by concentric mountain ranges that reach more than 3 km high in places. This huge circular basin, shown here in orange in this false-colored visible image from *Messenger*, is similar in size to the Moon's Mare Imbrium and spans more than half of Mercury's radius. *(NASA)*

Figure 8.22 shows what may have been a result of the last great geological event in the history of Mercury: an immense bull's-eye crater called the Caloris Basin, formed eons ago by the impact of a large asteroid. (The basin is so called because it lies in Mercury's "hot longitudes"---see Section 8.3---close to the planet's equator; *calor* is the Latin word for "heat.") Because of the orientation of the planet during *Mariner 10*'s flybys, only half of the basin was visible. The center of the crater is off the left-hand side of the photograph. Compare this basin with the Orientale Basin on the Moon (Figure 8.14a). The impact crater structures are quite similar, but even here there is a mystery: The patterns visible on the Caloris floor are unlike any seen on the Moon. Their origin, like the composition of the floor itself, is unknown.

So large was the impact that created the Caloris Basin that it apparently sent strong seismic waves reverberating throughout the entire planet. On the opposite side of



▲ FIGURE 8.23 **Weird Terrain** The refocusing of seismic waves after the Caloris Basin impact may have created the weird terrain on the opposite side of the planet.

Mercury from Caloris, there is a region of oddly rippled and wavy surface features, often referred to as *weird* (or *jumbled*) terrain. Scientists theorize that this terrain was produced when seismic waves from the Caloris impact traveled around the planet and converged on the diametrically opposite point, causing large-scale disruption of the surface there, as illustrated in Figure 8.23.

CONCEPT CHECK

✔ How do scarps on Mercury differ from geological faults on Earth?

8.7 Interiors

In Chapter 7 we saw how geologists combine bulk measurements of Earth's density, gravity, and magnetic field with seismic studies and mathematical models to build up a detailed model of the planet's interior. ∞ (Secs. 7.1, 7.3, 7.5) Planetary scientists attempt to do much the same with the Moon and Mercury, but since less detailed data are available, the conclusions are correspondingly less precise.

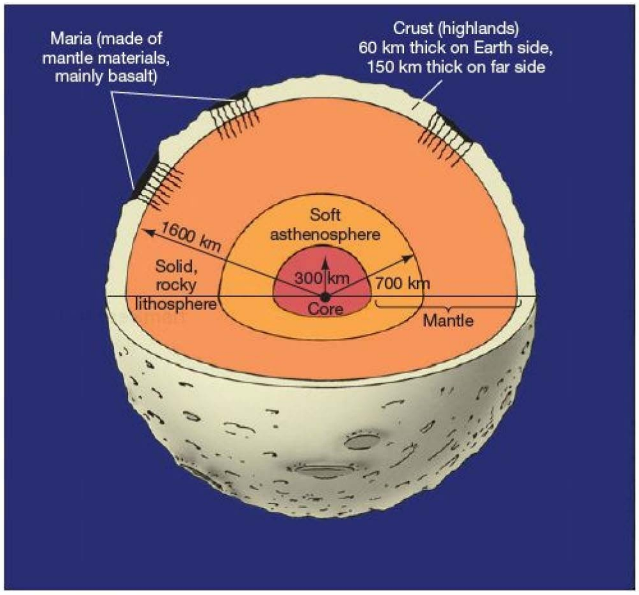
The Moon

The Moon's average density, about 3300 kg/m^3, is similar to the measured density of lunar surface rock, virtually eliminating any chance that the Moon has a large, massive, and very dense nickel–iron core like that of Earth. In fact, the low density implies that the entire Moon is actually deficient in iron and other heavy metals compared with their abundance on our planet.

There is no evidence for any large-scale lunar magnetic field. *Lunar Prospector* detected some very weak surface magnetic fields—less than a thousandth of Earth's field—apparently associated with some large impact basins, but these are not thought to be related to conditions in the lunar core. As we saw in Chapter 7, researchers think that planetary magnetism requires a rapidly rotating liquid metal core, like Earth's. ∞ (Sec. 7.5) Thus, the absence of a lunar magnetic field could be a consequence of the Moon's slow rotation, the absence of a liquid core, or both.

Data from the gravity experiment aboard *Lunar Prospector*, combined with measurements made by the probe's magnetometers as the Moon passed through Earth's magnetic "tail" (see Figure 7.18), imply that the Moon may have a small iron core perhaps 300 km in radius. Near the center, the temperature may be as low as 1500 K, too cool to melt rock. However, seismic data collected by sensitive equipment left on the surface by *Apollo* astronauts (see *Discovery 8-1*) suggest that the inner parts of the core may be at least partially molten, implying a somewhat higher temperature. Our knowledge of the Moon's deep interior is still quite limited.

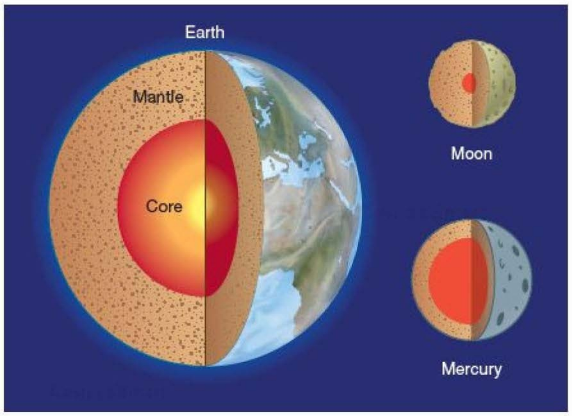
Based on a combination of seismic data, gravitational and magnetic measurements, and a good deal of mathematical modeling resting on assumptions about the Moon's interior composition, Figure 8.24 presents a



▲ FIGURE 8.24 **Lunar Interior** Cutaway diagram of the Moon. Unlike Earth's rocky lithosphere, the Moon's is very thick—nearly 1000 km. Below the lithosphere is the inner mantle, or lunar asthenosphere, a semisolid layer similar to the upper regions of Earth's mantle. At the center lies the core, which may be partly molten.

schematic diagram of the Moon's interior structure. The central core is surrounded by a roughly 400-km-thick inner mantle of semisolid rock having properties similar to Earth's asthenosphere. ∞ (Sec. 7.4) Above these regions lies an outer mantle of solid rock, some 900–950 km thick, topped by a 60- to 150-km crust (considerably thicker than that of Earth). Together, these layers constitute the Moon's lithosphere. Outside the core, the mantle seems to be of almost uniform density, although it is chemically differentiated (i.e., its chemical properties change from the deep interior to near the surface). The crust material, which forms the lunar highlands, is lighter than the mantle, which is similar in composition to the lunar maria.

The crust on the lunar far side is *thicker* than that on the side facing Earth. If we assume that lava takes the line of least resistance in getting to the surface, then we can readily understand why the far side of the Moon has no large maria: Volcanic activity did not occur on the far side simply because the crust was too thick to allow it to occur there.



▲ FIGURE 8.25 **Terrestrial Interiors** The internal structures of Earth, the Moon, and Mercury, drawn to the same scale. Note how large a fraction of Mercury's interior is the planet's core. Planetary interiors are key to the global subject of comparative planetology.

But *why* is the far-side crust thicker? The answer is probably related to Earth's gravitational pull. Just as heavier material tends to sink to the center of Earth, the denser lunar mantle tended to sink below the lighter crust in Earth's gravitational field. The effect of this tendency was that the crust and the mantle became slightly off center with respect to each other. The mantle was pulled a little closer to Earth, while the crust moved slightly away. Thus, the crust became thinner on the near side and thicker on the far side.

Mercury

Mercury's magnetic field, discovered by *Mariner 10,* is about a hundredth that of Earth. Actually, the discovery that Mercury has any magnetic field at all came as a surprise to planetary scientists. Having detected no magnetic field in the Moon (and, in fact, none in Venus or Mars, either), they had expected Mercury to have no measurable magnetism. Certainly, Mercury does not rotate rapidly, and it may lack a liquid metal core, yet a magnetic field undeniably surrounds it. Although weak, the field is strong enough to deflect the solar wind and create a small magnetosphere around the planet.

Scientists have no clear understanding of the origin of Mercury's magnetic field. If it is produced by ongoing dynamo action, as in Earth, then Mercury's core must be at least partially molten, and radar observations from Earth reported in 2007 appear to confirm this possibility. ∞ (Sec. 7.5) However, the absence of any recent surface geological activity suggests that the outer layers are solid to a considerable depth, as on the Moon. If the field is being generated dynamically, then Mercury's slow rotation may at least account for the field's weakness.

Before *Messenger*'s arrival, scientists thought it most likely that Mercury's magnetic field was a "fossil remnant" dating back to the distant past when the planet's core solidified. However, detailed observations by *Messenger* now suggest that the field is generated by dynamo action in the planet's core, as on Earth. ∞ (Sec. 7.5) In fact, an early surprise for the *Messenger* team was the degree to which the planet's magnetosphere changed between the first two flybys, in January and October 2008, suggesting that the planet's magnetic field might be much more dynamic than had previously been thought. How such a relatively strong field can be produced by a slowly rotating planet remains to be resolved.

Mercury's magnetic field and large average density together imply that the planet is differentiated. Even without the luxury of seismographs on the surface, we can infer that most of its interior must be dominated by a large, heavy, iron-rich core with a radius of perhaps 1800 km. Probably a less-dense lunar like mantle lies above this core, to a depth of about 500 to 600 km. Thus, about 40 percent of the volume of Mercury, or 60 percent of its mass, is contained in its iron core. The ratio of core volume to total planet volume is greater for Mercury than for any other object in the solar system. Figure 8.25 illustrates the relative sizes and internal structures of Earth, the Moon, and Mercury.

PROCESS OF SCIENCE CHECK

✔ Why would we not expect strong magnetic fields on the Moon or Mercury?

8.8 The Origin of the Moon

Over the years, many theories have been advanced to account for the origin of the Moon. However, both the similarities *and* the differences between the Moon and Earth conspire to confound many promising attempts to explain the Moon's existence.

Theories of Lunar Formation

One theory (the *sister*, or *coformation*, theory) suggests that the Moon formed as a separate object near Earth in much the same way as our own planet formed—the "blob" of material that eventually coalesced into Earth gave rise to the Moon at about the same time. The two objects thus formed as a double-planet system, each revolving about a common center of mass. Although once favored by many astronomers, this idea suffers from a major flaw: The Moon differs in both density and composition from Earth, making it hard to understand how both could have originated from the same preplanetary material.

A second theory (the *capture* theory) maintains that the Moon formed far from Earth and was later captured by it. In this way, the density and composition of the two objects need not be similar, for the Moon presumably materialized in a quite different region of the early solar system. The objection to this theory is that the Moon's capture would be an extraordinarily difficult event; it might even be an impossible one. Why? Because the mass of our Moon is so large relative to that of Earth. It is not that our Moon is the largest natural satellite in the solar system, but it is unusually large compared with its parent planet. Mathematical modeling suggests that it is quite implausible that Earth and the Moon could have interacted in just the right way for the Moon to have been captured during a close encounter sometime in the past. Furthermore, although there are indeed significant differences in composition between our world and its companion, there are also many similarities—particularly between the mantles of the two bodies—that make it unlikely that they formed entirely independently of one another.

A third, older, theory (the *daughter*, or fission, theory) speculates that the Moon originated out of Earth itself. The Pacific Ocean basin has often been mentioned as the place from which protolunar matter may have been torn—the result, perhaps, of the rapid spin of a young, molten Earth. Indeed, there are some chemical similarities between the matter in the Moon's outer mantle and that in Earth's Pacific basin. However, this theory offers no solution to the fundamental mystery of how Earth could have been spinning so fast that it ejected an object as large as our Moon. Also, computer simulations indicate that the ejection of the Moon into a stable orbit simply would not have occurred. As a result, the daughter theory, in this form at least, is no longer taken seriously.

MA ANIMATION/VIDEO Protoplanetary Collision

The Impact Theory

Today, many astronomers favor a hybrid of the capture and daughter themes. This idea—often called the impact theory—postulates a collision by a large, Mars-sized object with a youthful and molten Earth. Such collisions may have been quite frequent in the early solar system. ∞ (Sec. 6.7) The collision presumed by the impact theory would have been more a glancing blow than a direct impact. The matter dislodged from our planet then reassembled to form the Moon.

Computer simulations of such a catastrophic event show that most of the bits and pieces of splattered Earth could have coalesced into a stable orbit. Figure 8.26 shows some of the stages of one such calculation. If Earth had already formed an iron core by the time the collision occurred, then the Moon would indeed have ended up with a composition similar to that of Earth's mantle. During the collision, any iron core in the colliding object itself would have been left behind in Earth, eventually to become part of Earth's core. Thus, both the Moon's overall similarity to that of Earth's mantle and its lack of a dense central core are naturally explained.

Over the past two decades, planetary scientists have come to realize that collisions like this probably played important roles in the formation of all the terrestrial planets (see Chapter 15). Because of the randomness inherent in such events, as well as the Moon's unique status as the only large satellite in the inner solar system, it seems that the Moon may not provide a particularly useful model for studies of the other moons in the solar system. Instead, as we will see, a moon's properties depend greatly on the characteristics of its parent planet.

Nevertheless, the quest to understand the origin of the Moon highlights the interplay between theory and observation that characterizes modern science. ∞ (Sec. 1.2) Detailed data from generations of unmanned and manned lunar missions have allowed astronomers to discriminate between competing theories of the formation of the Moon, discarding some and modifying others. At the same time, the condensation theory of solar system formation provides a natural context in which the currently favored impact theory can occur. ∞ (Sec. 6.7) Indeed, without the idea that planets formed by collisions of smaller bodies, such an impact might well have been viewed as so improbable that the theory would never have gained ground.

Finally, do not think that every last detail of the Moon's formation is understood or agreed upon by experts. That is far from the case. Some important aspects of the Moon's physical and chemical makeup are still inadequately explained—for example, the degree to which the Moon melted during its formation and whether current models are actually consistent with the observed lunar composition. The impact theory may well not be the last word on the subject. Still, past experience of the scientific method gives us confidence that the many twists and turns still to come will in the end lead us to a more complete understanding of our nearest neighbor in space.

PROCESS OF SCIENCE CHECK

✔ How does the currently favored theory of the Moon's origin account for the Moon's observed lack of heavy materials compared with Earth and for the similarity in composition between the lunar crust and that of Earth?

8.9 Evolutionary History of the Moon and Mercury

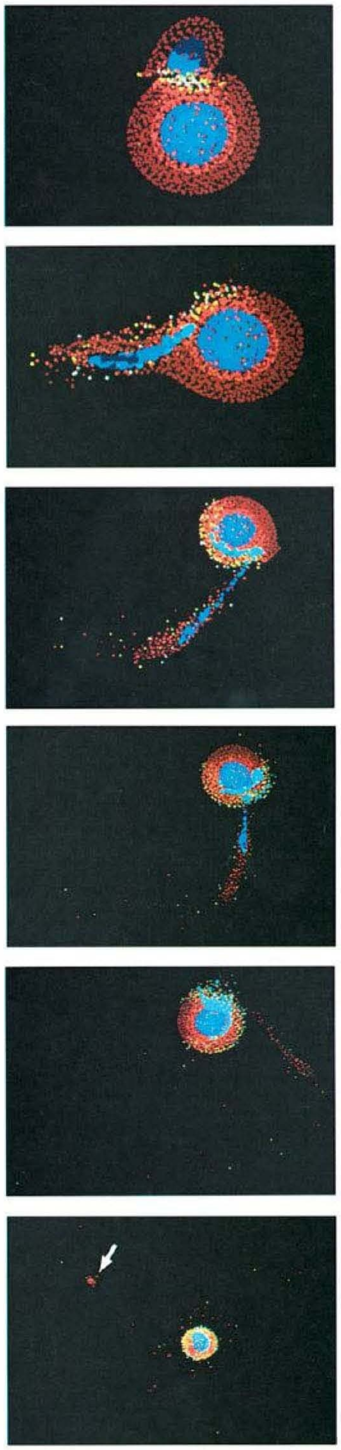
Given all the data, can we construct reasonably consistent histories of the Moon and Mercury? The answer seems to be yes. Many specifics are still debated, but a broad consensus exists. Planned future missions to both bodies will continue to test and refine the pictures presented below.

The Moon

The Moon formed about 4.6 billion years ago (see Chapter 15). The approximate age of the oldest rocks discovered in the lunar highlands is 4.4 billion years, so we know that at least part of the crust must already have solidified by that time and survived to the present. At its formation, the Moon was already depleted in heavy metals compared with Earth. Examine Figure 8.27 while studying the details that follow.

During the earliest phases of the Moon's existence—roughly the first half billion years or so—meteoritic bombardment must have been frequent enough to heat and remelt most of the *surface* layers of the Moon, perhaps to a depth of 400 km in places. The early solar system was surely populated with lots of interplanetary matter, much of it in the form of boulder-sized fragments that were capable of generating large amounts of energy upon colliding with planets and their moons. But the intense heat derived from such collisions could not have penetrated very far into the lunar interior: Rock simply does not conduct heat well.

This situation resembles the surface melting we suspect occurred on Earth from meteoritic impacts during the first



◀ **FIGURE 8.26 Moon Formation** This sequence shows a simulated collision between Earth and an object the size of Mars. The sequence proceeds from top to bottom and zooms out dramatically. The arrow in the final frame shows the newly formed Moon. Red and blue colors represent rocky and metallic regions, respectively, and the direction of motion of the blue material in frames 2, 3, 4, and 5 is toward Earth. Note how most of the impactor's metallic core becomes part of Earth, leaving the Moon composed mainly of rocky material. *(W. Benz)*

(a) 4 billion years ago

(b) 3 billion years ago

(c) Today

▲ **FIGURE 8.27 Lunar Evolution** Paintings of the Moon (a) about 4 billion years ago, after much of the meteoritic bombardment had subsided and the surface had solidified somewhat; (b) about 3 billion years ago, after molten lava had made its way up through surface fissures to fill the low-lying impact basins and create the smooth maria; and (c) today, with much of the originally smooth maria now heavily pitted with craters formed at various times within the past 3 billion years. *(U.S. Geological Survey)*

billion years or so. But the Moon is much less massive than Earth and did not contain enough radioactive elements to heat it much further. Radioactivity probably heated the Moon a little, but not sufficiently to transform it from a warm, semisolid object to a completely liquid one. The chemical differentiation now inferred in the Moon's interior must have occurred during this period. If the Moon has a small iron core, that core also formed at this time.

About 3.9 billion years ago, around the time that Earth's crust solidified, the heaviest phase of the meteoritic bombardment ceased. The Moon was left with a solid crust, which would ultimately become the highlands, dented with numerous large basins, soon to flood with lava and become the maria (Figure 8.27a). Between 3.9 and 3.2 billion years ago, lunar volcanism filled the maria with the basaltic material we see today. The age of the youngest maria—3.2 billion years—indicates the time when the volcanic activity subsided. The maria are the sites of the last extensive lava flows on the Moon, over 3 billion years ago. Their smoothness, compared with the older, more rugged highlands, disguises their great age.

Small objects cool more rapidly than large ones because their interior is closer to the surface, on average. Being so small, the Moon rapidly lost its internal heat to space. As a consequence, it cooled much faster than Earth. As the Moon cooled, the volcanic activity ended and the thickness of the solid surface layer increased. With the exception of a few meters of surface erosion from eons of meteoritic bombardment (Figure 8.27c), the lunar landscape has remained more or less structurally frozen for the past 3 billion years. The Moon is dead now, and it has been dead for a long time.

Mercury

Like the Moon, Mercury seems to have been a geologically dead world for much of the past 4 billion years. On both the Moon and Mercury, the absence of ongoing geological activity is a consequence of a thick, solid mantle that prevents volcanism or tectonic motion. Because of the *Apollo* program, the Moon's early history is much better understood than Mercury's, which remains somewhat speculative. Indeed, what we do know about Mercury's history is gleaned mostly through comparison with the Moon.

When Mercury formed some 4.6 billion years ago, it was already depleted of lighter, rocky material. We will see later that this was largely a consequence of its location in the hot inner regions of the early solar system, although it is possible that a collision stripped away some of the planet's light mantle. During the next half-billion years, Mercury melted and differentiated, like the other terrestrial worlds. It suffered the same intense meteoritic bombardment as the Moon. Being more massive than the Moon, Mercury cooled more slowly, so its crust was thinner and volcanic activity more common at early times. More craters were erased, resulting in the intercrater plains found by *Mariner 10*.

As Mercury's large iron core formed and then cooled, the planet began to shrink, compressing the crust. This compression produced the scarps seen on Mercury's surface and may have prematurely terminated volcanic activity by squeezing shut the cracks and fissures on the surface. Thus, the extensive volcanic outflows that formed the lunar maria did not take place on Mercury. Despite its larger mass and greater internal temperature, Mercury has probably been geologically inactive even longer than the Moon.

CHAPTER REVIEW

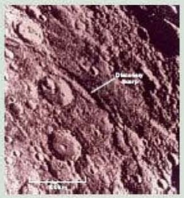
SUMMARY

1 The Moon orbits Earth; Mercury is the closest planet to the Sun. Both the Moon and Mercury are airless, virtually unchanging worlds that exhibit extremes in temperature. Mercury has no permanent atmosphere, although it does have a thin envelope of gas temporarily trapped from the solar wind. Both bodies are smaller and less massive than Earth and have weaker gravities. The absence of atmospheric blankets results in hot dayside temperatures and cold nightside temperatures on the Moon and Mercury. Sunlight strikes the polar regions of both the Moon and Mercury at such an oblique angle that temperatures there are very low, with the result that both bodies may have significant amounts of water ice near their poles.

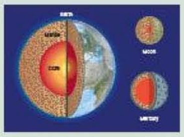
2 The main surface features on the Moon are the dark **maria (p. 186)** and the lighter colored **highlands (p. 186)**. Highland rocks are less dense than rocks from the maria and are thought to represent the Moon's crust. Maria rocks are thought to have originated in the lunar mantle. The surfaces of both the Moon and Mercury are covered with **craters (p. 186)** of all sizes, caused by meteoroids striking from space. Lunar dust, called regolith, is made mostly of pulverized lunar rock, mixed with a small amount of material from impacting meteorites.

3 The tidal interaction between Earth and the Moon is responsible for the Moon's **synchronous orbit (p. 189)**, in which the same side of the Moon always faces our planet. The large lunar equatorial bulge probably indicates that the Moon once rotated more rapidly and orbited closer to Earth. Mercury's rotation rate is strongly influenced by the tidal effect of the Sun. Because of Mercury's eccentric orbit, the planet rotates not synchronously, but exactly three times for every two orbits around the Sun. The condition in which a body's rotation rate is simply related to its orbital period around some other body is known as **spin–orbit resonance (p. 193)**.

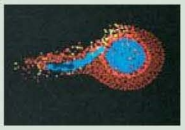
4 Meteoritic impacts are the main source of erosion on the surfaces of both the Moon and Mercury. The lunar highlands are older than the maria and are much more heavily cratered. The rate at which craters are formed decreases rapidly with increasing crater size. By measuring the ages of lunar rocks returned to Earth by *Apollo* astronauts, astronomers have deduced the rate of cratering in the past. They then use the amount of cratering to deduce the ages of regions on the Moon (and elsewhere) from which surface samples are unavailable.



5 Evidence for past volcanic activity on the Moon is found in the form of crater chains and solidified lava channels called **rilles (p. 200)**. Mercury's surface features bear a striking similarity to those of the Moon. The planet is heavily cratered, much like the lunar highlands. Among the differences between Mercury and the Moon are Mercury's lack of lunarlike maria, its extensive **intercrater plains (p. 200)**, and the great cracks, or **scarps (p. 201)**, in its crust. The plains were caused by extensive lava flows early in Mercury's history. The scarps were apparently formed when the planet's core cooled and shrank, causing the surface to crack. Mercury has a large impact crater called the Caloris Basin, whose diameter is comparable to the radius of the planet. The impact that formed the crater apparently sent violent shock waves around the entire planet, buckling the crust on the opposite side.



6 The Moon's average density is not much greater than that of its surface rocks, probably because the Moon cooled more rapidly than the larger Earth and solidified sooner, so there was less time for differentiation to occur, although the Moon likely has a small iron-rich core. The lunar crust is too thick and the mantle too cool for plate tectonics to occur. Mercury's average density is considerably greater—similar to that of Earth—implying that Mercury contains a large high-density core, probably composed primarily of iron. The Moon has no measurable large-scale magnetic field, a consequence of its slow rotation and lack of a molten metallic core. Mercury's weak magnetic field seems to have been "frozen in" long ago, when the planet's iron core solidified.



7 The most likely explanation for the formation of the Moon is that the newly formed Earth was struck by a large (Mars-sized) object. Part of the colliding body remained behind as part of our planet. The rest ended up in orbit as the Moon.

8 The absence of a lunar atmosphere and any present-day lunar volcanic activity are both consequences of the Moon's small size. Lunar gravity is too weak to retain any gases, and lunar volcanism was stifled by the Moon's cooling mantle shortly after extensive lava flows formed the maria more than 3 billion years ago. The crust on the far side of the Moon is substantially thicker than the crust on the near side. As a result, there are almost no maria on the lunar far side. Mercury's evolutionary path was similar to that of the Moon for half a billion years after they both formed. Mercury's volcanic period probably ended before that of the Moon.