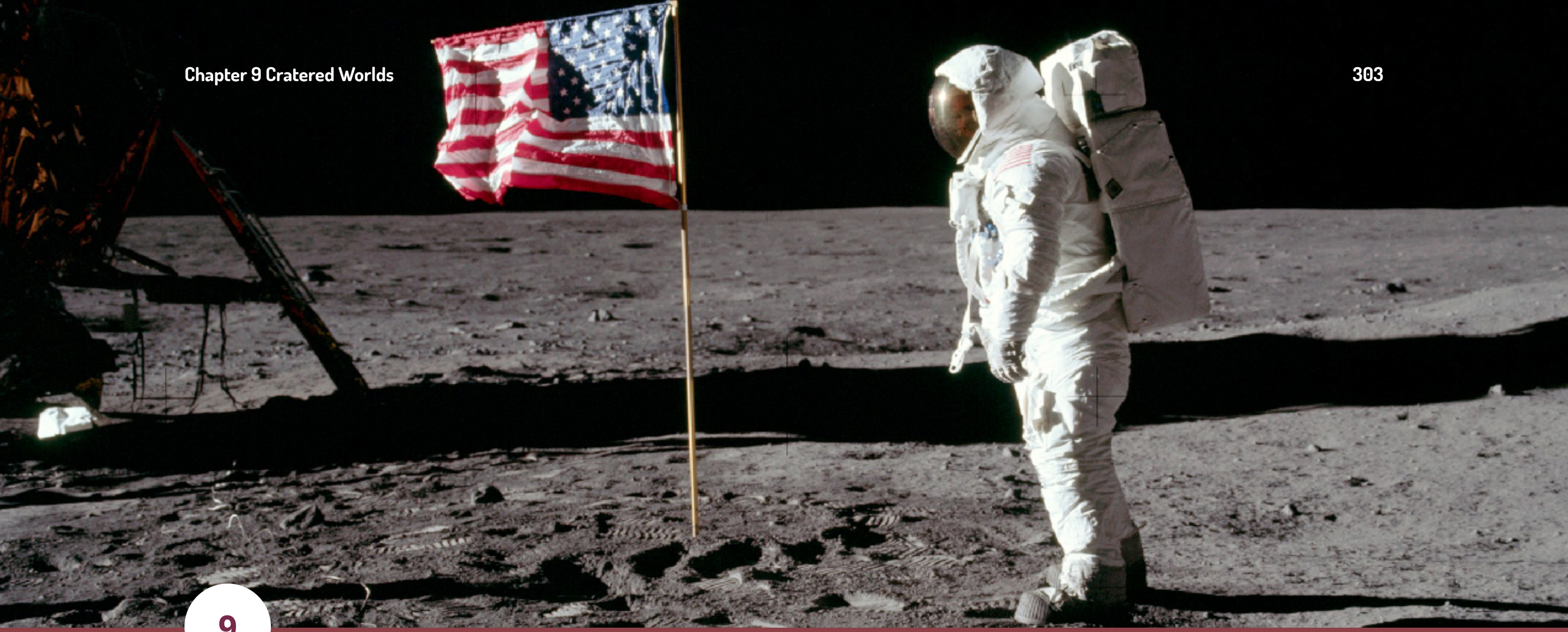

9

CRATERED WORLDS

Figure 9.1 Apollo 11 Astronaut Edwin "Buzz" Aldrin on the Surface of the Moon. Because there is no atmosphere, ocean, or geological activity on the Moon today, the footprints you see in the image will likely be preserved in the lunar soil for millions of years (credit: modification of work by NASA/ Neil A. Armstrong).

Chapter Outline

Thinking Ahead

The Moon is the only other world human beings have ever visited. What is it like to stand on the surface of our natural satellite? And what can we learn from going there and bringing home pieces of a different world?

We begin our discussion of the planets as cratered worlds with two relatively simple objects: the Moon and Mercury. Unlike Earth, the Moon is geologically dead, a place that has exhausted its internal energy sources. Because its airless surface preserves events that happened long ago, the Moon provides a window on earlier epochs of solar system history. The planet Mercury is in many ways similar to the Moon, which is why the two are discussed together: both are relatively small, lacking in atmospheres, deficient in geological activity, and dominated by the effects of impact cratering. Still, the processes that have molded their surfaces are not unique to these two worlds. We shall see that they have acted on many other members of the planetary system as well.

9.1 GENERAL PROPERTIES OF THE MOON

Learning Objectives

By the end of this section, you will be able to:

- Discuss what has been learned from both manned and robotic lunar exploration
- Describe the composition and structure of the Moon

The Moon has only one-eightieth the mass of Earth and about one-sixth Earth's surface gravity—too low to retain an atmosphere (**Figure 9.2**). Moving molecules of a gas can escape from a planet just the way a rocket does, and the lower the gravity, the easier it is for the gas to leak away into space. While the Moon can acquire a temporary atmosphere from impacting comets, this atmosphere is quickly lost by freezing onto the surface or by escape to surrounding space. The Moon today is dramatically deficient in a wide range of *volatiles*, those elements and compounds that evaporate at relatively low temperatures. Some of the Moon's properties are summarized in **Table 9.1**, along with comparative values for Mercury.

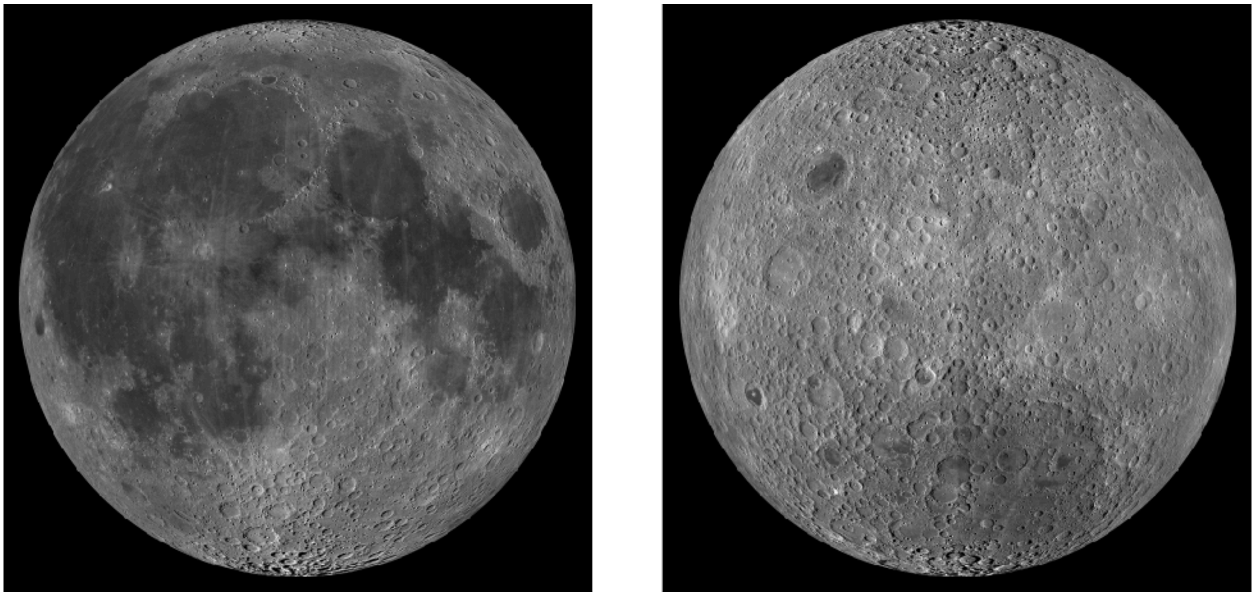

Figure 9.2 Two Sides of the Moon. The left image shows part of the hemisphere that faces Earth; several dark maria are visible. The right image shows part of the hemisphere that faces away from Earth; it is dominated by highlands. The resolution of this image is several kilometers, similar to that of high-powered binoculars or a small telescope. (credit: modification of work by NASA/GSFC/Arizona State University)

Properties of the Moon and Mercury

Property	Moon	Mercury
Mass (Earth = 1)	0.0123	0.055
Diameter (km)	3476	4878
Density (g/cm^3)	3.3	5.4
Surface gravity (Earth = 1)	0.17	0.38
Escape velocity (km/s)	2.4	4.3
Rotation period (days)	27.3	58.65

Table 9.1

Properties of the Moon and Mercury

Property	Moon	Mercury
Surface area (Earth = 1)	0.27	0.38

Table 9.1

Exploration of the Moon

Most of what we know about the Moon today derives from the US Apollo program, which sent nine piloted spacecraft to our satellite between 1968 and 1972, landing 12 astronauts on its surface (**Figure 9.1**). Before the era of spacecraft studies, astronomers had mapped the side of the Moon that faces Earth with telescopic resolution of about 1 kilometer, but lunar geology hardly existed as a scientific subject. All that changed beginning in the early 1960s. Initially, Russia took the lead in lunar exploration with Luna 3, which returned the first photos of the lunar far side in 1959, and then with Luna 9, which landed on the surface in 1966 and transmitted pictures and other data to Earth. However, these efforts were overshadowed on July 20, 1969, when the first American astronaut set foot on the Moon.

Table 9.2 summarizes the nine Apollo flights: six that landed and three others that circled the Moon but did not land. The initial landings were on flat plains selected for safety reasons. But with increasing experience and confidence, NASA targeted the last three missions to more geologically interesting locales. The level of scientific exploration also increased with each mission, as the astronauts spent longer times on the Moon and carried more elaborate equipment. Finally, on the last Apollo landing, NASA included one scientist, geologist Jack Schmitt, among the astronauts (**Figure 9.3**).

Apollo Flights to the Moon

Flight	Date	Landing Site	Main Accomplishment
Apollo 8	Dec. 1968	—	First humans to fly around the Moon
Apollo 10	May 1969	—	First spacecraft rendezvous in lunar orbit
Apollo 11	July 1969	Mare Tranquillitatis	First human landing on the Moon; 22 kilograms of samples returned
Apollo 12	Nov. 1969	Oceanus Procellarum	First Apollo Lunar Surface Experiment Package (ALSEP); visit to Surveyor 3 lander
Apollo 13	Apr. 1970	—	Landing aborted due to explosion in service module
Apollo 14	Jan. 1971	Mare Nubium	First “rickshaw” on the Moon
Apollo 15	July 1971	Mare Imbrium/ Hadley	First “rover;” visit to Hadley Rille; astronauts traveled 24 kilometers

Table 9.2

Apollo Flights to the Moon

Flight	Date	Landing Site	Main Accomplishment
Apollo 16	Apr. 1972	Descartes	First landing in highlands; 95 kilograms of samples returned
Apollo 17	Dec. 1972	Taurus-Littrow highlands	Geologist among the crew; 111 kilograms of samples returned

Table 9.2

Figure 9.3 Scientist on the Moon. Geologist (and later US senator) Harrison "Jack" Schmitt in front of a large boulder in the Littrow Valley at the edge of the lunar highlands. Note how black the sky is on the airless Moon. No stars are visible because the surface is brightly lit by the Sun, and the exposure therefore is not long enough to reveal stars.

In addition to landing on the lunar surface and studying it at close range, the Apollo missions accomplished three objectives of major importance for lunar science. First, the astronauts collected nearly 400 kilograms of samples for detailed laboratory analysis on Earth (**Figure 9.4**). These samples have revealed as much about the Moon and its history as all other lunar studies combined. Second, each Apollo landing after the first one deployed an Apollo Lunar Surface Experiment Package (ALSEP), which continued to operate for years after the astronauts departed. Third, the orbiting Apollo command modules carried a wide range of instruments to photograph and analyze the lunar surface from above.

Figure 9.4 Handling Moon Rocks. Lunar samples collected in the Apollo Project are analyzed and stored in NASA facilities at the Johnson Space Center in Houston, Texas. Here, a technician examines a rock sample using gloves in a sealed environment to avoid contaminating the sample. (credit: NASA JSC)

The last human left the Moon in December 1972, just a little more than three years after Neil Armstrong took his "giant leap for mankind." The program of lunar exploration was cut off midstride due to political and economic pressures. It had cost just about $100 per American, spread over 10 years—the equivalent of one large pizza per person per year. Yet for many people, the Moon landings were one of the central events in twentieth-century history.

The giant Apollo rockets built to travel to the Moon were left to rust on the lawns of NASA centers in Florida, Texas, and Alabama, although recently, some have at least been moved indoors to museums (**Figure 9.5**). Today, neither NASA nor Russia have plans to send astronauts to the Moon, and China appears to be the nation most likely to attempt this feat. (In a bizarre piece of irony, a few people even question whether we went to the Moon at all, proposing instead that the Apollo program was a fake, filmed on a Hollywood sound stage. See the **Link to Learning** box below for some scientists' replies to such claims.) However, scientific interest in the Moon is stronger than ever, and more than half a dozen scientific spacecraft—sent from NASA, ESA, Japan, India, and China—have orbited or landed on our nearest neighbor during the past decade.

LINK TO LEARNING

Read **The Great Moon Hoax (https://openstax.org/l/30greatmoonhoax)** about the claim that NASA never succeeded in putting people on the Moon.

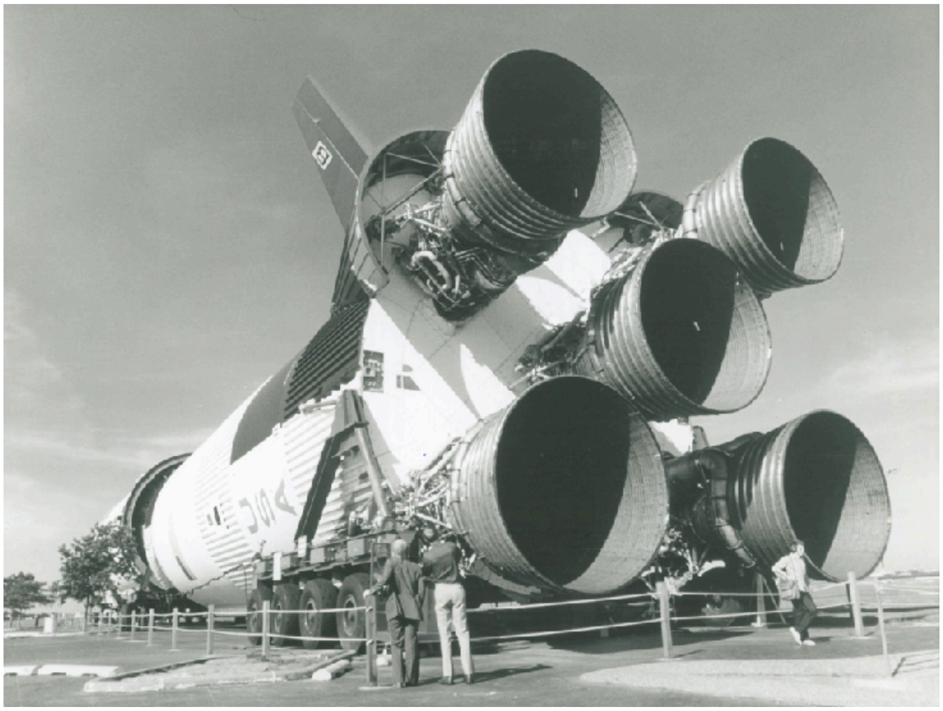

Figure 9.5 Moon Rocket on Display. One of the unused Saturn 5 rockets built to go to the Moon is now a tourist attraction at NASA's Johnson Space Center in Houston, although it has been moved indoors since this photo was taken. (credit: modification of work by David Morrison)

Lunar exploration has become an international enterprise with many robotic spacecraft focusing on lunar science. The USSR sent a number in the 1960s, including robot sample returns. Table 9.3 lists some of the most recent lunar missions.

Some International Missions to the Moon

Launch Year	Spacecraft	Type of Mission	Agency
1994	Clementine	Orbiter	US (USAF/NASA)
1998	Lunar Prospector	Orbiter	US (NASA)
2003	SMART-1	Orbiter	Europe (ESA)
2007	SELENE 1	Orbiter	Japan (JAXA)
2007	Chang'e 1	Orbiter	China (CNSA)
2008	Chandrayaan-1	Orbiter	India (ISRO)
2009	LRO	Orbiter	US (NASA)
2009	LCROSS	Impactor	US (NASA)

Table 9.3

Some International Missions to the Moon

Launch Year	Spacecraft	Type of Mission	Agency
2010	Chang'e 2	Orbiter	China (CNSA)
2011	GRAIL	Twin orbiters	US (NASA)
2013	LADEE	Orbiter	US (NASA)
2013	Chang'e 3	Lander/Rover	China (CNSA)

Table 9.3

Composition and Structure of the Moon

The composition of the Moon is not the same as that of Earth. With an average density of only 3.3 g/cm^3, the Moon must be made almost entirely of silicate rock. Compared to Earth, it is depleted in iron and other metals. It is as if the Moon were composed of the same silicates as Earth's mantle and crust, with the metals and the volatiles selectively removed. These differences in composition between Earth and Moon provide important clues about the origin of the Moon, a topic we will cover in detail later in this chapter.

Studies of the Moon's interior carried out with seismometers taken to the Moon as part of the Apollo program confirm the absence of a large metal core. The twin GRAIL spacecraft launched into lunar orbit in 2011 provided even more precise tracking of the interior structure. We also know from the study of lunar samples that water and other volatiles have been depleted from the lunar crust. The tiny amounts of water detected in these samples were originally attributed to small leaks in the container seal that admitted water vapor from Earth's atmosphere. However, scientists have now concluded that some chemically bound water is present in the lunar rocks.

Most dramatically, water ice has been detected in permanently shadowed craters near the lunar poles. In 2009, NASA crashed a small spacecraft called the Lunar Crater Observation and Sensing Satellite (LCROSS) into the crater Cabeus near the Moon's south pole. The impact at 9,000 kilometers per hour released energy equivalent to 2 tons of dynamite, blasting a plume of water vapor and other chemicals high above the surface. This plume was visible to telescopes in orbit around the Moon, and the LCROSS spacecraft itself made measurements as it flew through the plume. A NASA spacecraft called the Lunar Reconnaissance Orbiter (LRO) also measured the very low temperatures inside several lunar craters, and its sensitive cameras were even able to image crater interiors by starlight.

The total quantity of water ice in the Moon's polar craters is estimated to be hundreds of billions of tons. As liquid, this would only be enough water to fill a lake 100 miles across, but compared with the rest of the dry lunar crust, so much water is remarkable. Presumably, this polar water was carried to the Moon by comets and asteroids that hit its surface. Some small fraction of the water froze in a few extremely cold regions (cold traps) where the Sun never shines, such as the bottom of deep craters at the Moon's poles. One reason this discovery could be important is that it raises the possibility of future human habitation near the lunar poles, or even of a lunar base as a way-station on routes to Mars and the rest of the solar system. If the ice could be mined, it would yield both water and oxygen for human support, and it could be broken down into hydrogen and oxygen, a potent rocket fuel.

9.2 THE LUNAR SURFACE

Learning Objectives

By the end of this section, you will be able to:

- Differentiate between the major surface features of the Moon
- Describe the history of the lunar surface
- Describe the properties of the lunar “soil”

General Appearance

If you look at the Moon through a telescope, you can see that it is covered by impact craters of all sizes. The most conspicuous of the Moon’s surface features—those that can be seen with the unaided eye and that make up the feature often called “the man in the Moon”—are vast splotches of darker lava flows.

Centuries ago, early lunar observers thought that the Moon had continents and oceans and that it was a possible abode of life. They called the dark areas “seas” (*maria* in Latin, or *mare* in the singular, pronounced “mah ray”). Their names, Mare Nubium (Sea of Clouds), Mare Tranquillitatis (Sea of Tranquility), and so on, are still in use today. In contrast, the “land” areas between the seas are not named. Thousands of individual craters have been named, however, mostly for great scientists and philosophers (**Figure 9.6**). Among the most prominent craters are those named for Plato, Copernicus, Tycho, and Kepler. Galileo only has a small crater, however, reflecting his low standing among the Vatican scientists who made some of the first lunar maps.

We know today that the resemblance of lunar features to terrestrial ones is superficial. Even when they look somewhat similar, the origins of lunar features such as craters and mountains are very different from their terrestrial counterparts. The Moon’s relative lack of internal activity, together with the absence of air and water, make most of its geological history unlike anything we know on Earth.

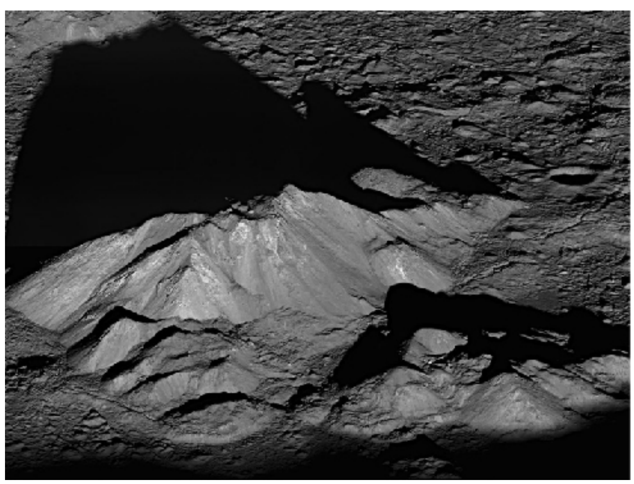

Figure 9.6 Sunrise on the Central Mountain Peaks of Tycho Crater, as Imaged by the NASA Lunar Reconnaissance Orbiter. Tycho, about 82 kilometers in diameter, is one of the youngest of the very large lunar craters. The central mountain rises 12 kilometers above the crater floor. (credit: modification of work by NASA/Goddard/Arizona State University)

Lunar History

To trace the detailed history of the Moon or of any planet, we must be able to estimate the ages of individual rocks. Once lunar samples were brought back by the Apollo astronauts, the radioactive dating techniques that had been developed for Earth were applied to them. The solidification ages of the samples ranged from about

3.3 to 4.4 billion years old, substantially older than most of the rocks on Earth. For comparison, as we saw in the chapter on **Earth, Moon, and Sky**, both Earth and the Moon were formed between 4.5 and 4.6 billion years ago.

Most of the crust of the Moon (83%) consists of silicate rocks called *anorthosites*; these regions are known as the lunar **highlands**. They are made of relatively low-density rock that solidified on the cooling Moon like slag floating on the top of a smelter. Because they formed so early in lunar history (between 4.1 and 4.4 billion years ago), the highlands are also extremely heavily cratered, bearing the scars of all those billions of years of impacts by interplanetary debris (**Figure 9.7**).

Figure 9.7 Lunar Highlands. The old, heavily cratered lunar highlands make up 83% of the Moon’s surface. (credit: Apollo 11 Crew, NASA)

Unlike the mountains on Earth, the Moon’s highlands do not have any sharp folds in their ranges. The highlands have low, rounded profiles that resemble the oldest, most eroded mountains on Earth (**Figure 9.8**). Because there is no atmosphere or water on the Moon, there has been no wind, water, or ice to carve them into cliffs and sharp peaks, the way we have seen them shaped on Earth. Their smooth features are attributed to gradual erosion, mostly due to impact cratering from meteorites.

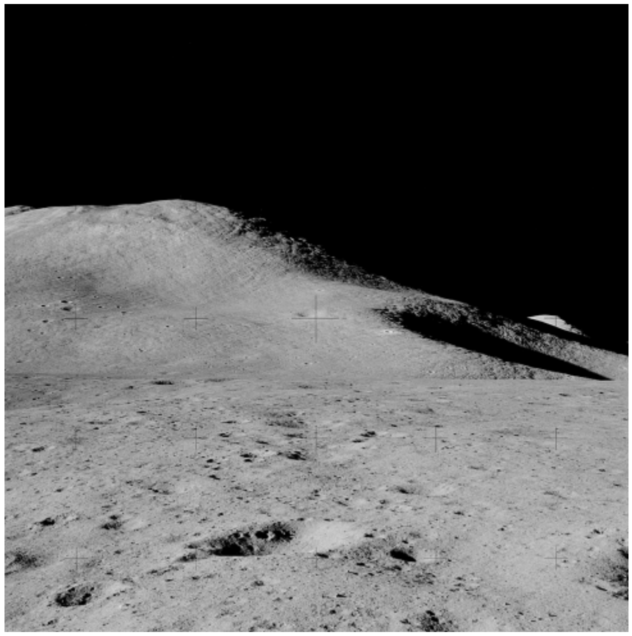

Figure 9.8 Lunar Mountain. This photo of Mt. Hadley on the edge of Mare Imbrium was taken by Dave Scott, one of the Apollo 15 astronauts. Note the smooth contours of the lunar mountains, which have not been sculpted by water or ice. (credit: NASA/Apollo Lunar Surface Journal)

The maria are much less cratered than the highlands, and cover just 17% of the lunar surface, mostly on the side of the Moon that faces Earth (**Figure 9.9**).

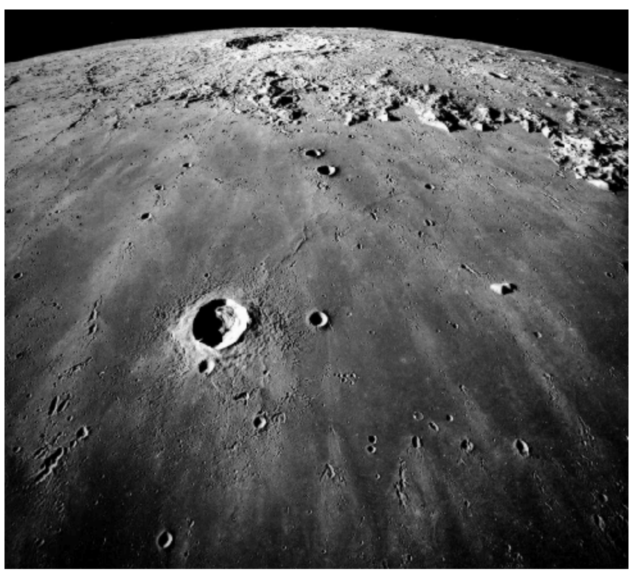

Figure 9.9 Lunar Maria. About 17% of the Moon's surface consists of the maria—flat plains of basaltic lava. This view of Mare Imbrium also shows numerous secondary craters and evidence of material ejected from the large crater Copernicus on the upper horizon. Copernicus is an impact crater almost 100 kilometers in diameter that was formed long after the lava in Imbrium had already been deposited. (credit: NASA, Apollo 17)

Today, we know that the maria consist mostly of dark-colored basalt (volcanic lava) laid down in volcanic eruptions billions of years ago. Eventually, these lava flows partly filled the huge depressions called *impact basins*, which had been produced by collisions of large chunks of material with the Moon relatively early in its history. The basalt on the Moon (**Figure 9.10**) is very similar in composition to the crust under the oceans of Earth or to the lavas erupted by many terrestrial volcanoes. The youngest of the lunar impact basins is Mare

Orientale, shown in **Figure 9.11**.

Figure 9.10 Rock from a Lunar Mare. In this sample of basalt from the mare surface, you can see the holes left by gas bubbles, which are characteristic of rock formed from lava. All lunar rocks are chemically distinct from terrestrial rocks, a fact that has allowed scientists to identify a few lunar samples among the thousands of meteorites that reach Earth. (credit: modification of work by NASA)

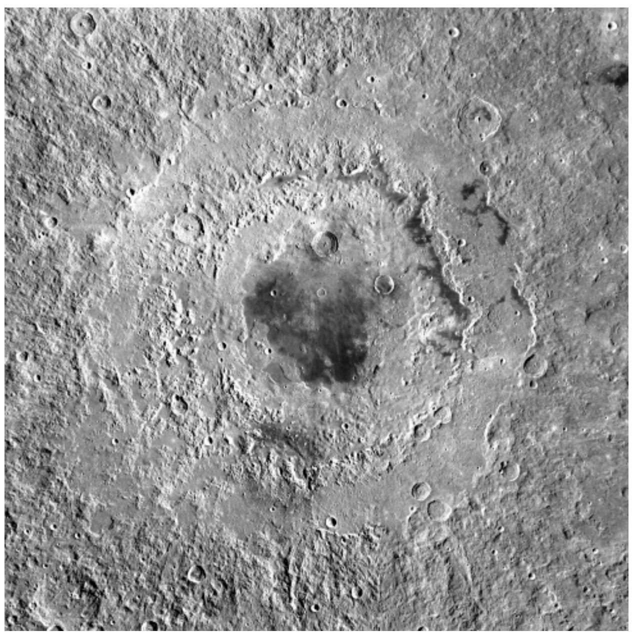

Figure 9.11 Mare Orientale. The youngest of the large lunar impact basins is Orientale, formed 3.8 billion years ago. Its outer ring is about 1000 kilometers in diameter, roughly the distance between New York City and Detroit, Michigan. Unlike most of the other basins, Orientale has not been completely filled in with lava flows, so it retains its striking “bull’s-eye” appearance. It is located on the edge of the Moon as seen from Earth. (credit: NASA)

Volcanic activity may have begun very early in the Moon’s history, although most evidence of the first half billion years is lost. What we do know is that the major mare volcanism, which involved the release of lava from hundreds of kilometers below the surface, ended about 3.3 billion years ago. After that, the Moon’s interior cooled, and volcanic activity was limited to a very few small areas. The primary forces altering the surface come from the outside, not the interior.

On the Lunar Surface

“The surface is fine and powdery. I can pick it up loosely with my toe. But I can see the footprints of my boots and the treads in the fine sandy particles.” —Neil Armstrong, Apollo 11 astronaut, immediately after stepping onto the

Moon for the first time.

The surface of the Moon is buried under a fine-grained soil of tiny, shattered rock fragments. The dark basaltic dust of the lunar maria was kicked up by every astronaut footstep, and thus eventually worked its way into all of the astronauts' equipment. The upper layers of the surface are porous, consisting of loosely packed dust into which their boots sank several centimeters (**Figure 9.12**). This lunar dust, like so much else on the Moon, is the product of impacts. Each cratering event, large or small, breaks up the rock of the lunar surface and scatters the fragments. Ultimately, billions of years of impacts have reduced much of the surface layer to particles about the size of dust or sand.

Figure 9.12 Footprint on Moon Dust. Apollo photo of an astronaut's boot print in the lunar soil. (credit: NASA)

In the absence of any air, the lunar surface experiences much greater temperature extremes than the surface of Earth, even though Earth is virtually the same distance from the Sun. Near local noon, when the Sun is highest in the sky, the temperature of the dark lunar soil rises above the boiling point of water. During the long lunar night (which, like the lunar day, lasts two Earth weeks[1]), the temperature drops to about 100 K (–173 °C). The extreme cooling is a result not only of the absence of air but also of the porous nature of the Moon's dusty soil, which cools more rapidly than solid rock would.

LINK TO LEARNING

Learn how the moon's craters and maria were formed by watching a **video produced by NASA's Lunar Reconnaissance Orbiter (LRO) team (https://openstax.org/l/30mooncratersfo)** about the evolution of the Moon, tracing it from its origin about 4.5 billion years ago to the Moon we see today. See a simulation of how the Moon's craters and maria were formed through periods of impact, volcanic activity, and heavy bombardment.

1 You can see the cycle of day and night on the side of the Moon facing us in the form of the Moon's phases. It takes about 14 days for the side of the Moon facing us to go from full moon (all lit up) to new moon (all dark). There is more on this in Chapter 4: Earth, Moon, and Sky.

9.3 IMPACT CRATERS

Learning Objectives

By the end of this section, you will be able to:

- Compare and contrast ideas about how lunar craters form
- Explain the process of impact crater formation
- Discuss the use of crater counts to determine relative ages of lunar landforms

The Moon provides an important benchmark for understanding the history of our planetary system. Most solid worlds show the effects of impacts, often extending back to the era when a great deal of debris from our system's formation process was still present. On Earth, this long history has been erased by our active geology. On the Moon, in contrast, most of the impact history is preserved. If we can understand what has happened on the Moon, we may be able to apply this knowledge to other worlds. The Moon is especially interesting because it is not just any moon, but *our* Moon—a nearby world that has shared the history of Earth for more than 4 billion years and preserved a record that, for Earth, has been destroyed by our active geology.

Volcanic Versus Impact Origin of Craters

Until the middle of the twentieth century, scientists did not generally recognize that lunar craters were the result of impacts. Since impact craters are extremely rare on Earth, geologists did not expect them to be the major feature of lunar geology. They reasoned (perhaps unconsciously) that since the craters we have on Earth are volcanic, the lunar craters must have a similar origin.

One of the first geologists to propose that lunar craters were the result of impacts was Grove K. Gilbert, a scientist with the US Geological Survey in the 1890s. He pointed out that the large lunar craters—mountain-rimmed, circular features with floors generally below the level of the surrounding plains—are larger and have different shapes from known volcanic craters on Earth. Terrestrial volcanic craters are smaller and deeper and almost always occur at the tops of volcanic mountains (Figure 9.13). The only alternative to explain the Moon's craters was an impact origin. His careful reasoning, although not accepted at the time, laid the foundations for the modern science of lunar geology.

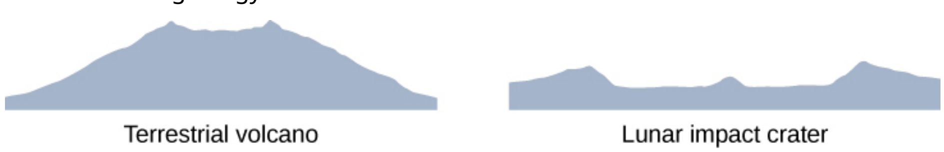

Figure 9.13 Volcanic and Impact Craters. Profiles of a typical terrestrial volcanic crater and a typical lunar impact crater are quite different.

Gilbert concluded that the lunar craters were produced by impacts, but he didn't understand why all of them were circular and not oval. The reason lies in the escape velocity, the minimum speed that a body must reach to permanently break away from the gravity of another body; it is also the minimum speed that a projectile approaching Earth or the Moon will hit with. Attracted by the gravity of the larger body, the incoming chunk strikes with at least escape velocity, which is 11 kilometers per second for Earth and 2.4 kilometers per second (5400 miles per hour) for the Moon. To this escape velocity is added whatever speed the projectile already had with respect to Earth or Moon, typically 10 kilometers per second or more.

At these speeds, the energy of impact produces a violent *explosion* that excavates a large volume of material in a symmetrical way. Photographs of bomb and shell craters on Earth confirm that explosion craters are always essentially circular. Only following World War I did scientists recognize the similarity between impact craters and explosion craters, but, sadly, Gilbert did not live to see his impact hypothesis widely accepted.

The Cratering Process

Let's consider how an impact at these high speeds produces a crater. When such a fast projectile strikes a planet, it penetrates two or three times its own diameter before stopping. During these few seconds, its energy of motion is transferred into a shock wave (which spreads through the target body) and into heat (which vaporizes most of the projectile and some of the surrounding target). The shock wave fractures the rock of the target, while the expanding silicate vapor generates an explosion similar to that of a nuclear bomb detonated at ground level (**Figure 9.14**). The size of the excavated crater depends primarily on the speed of impact, but generally it is 10 to 15 times the diameter of the projectile.

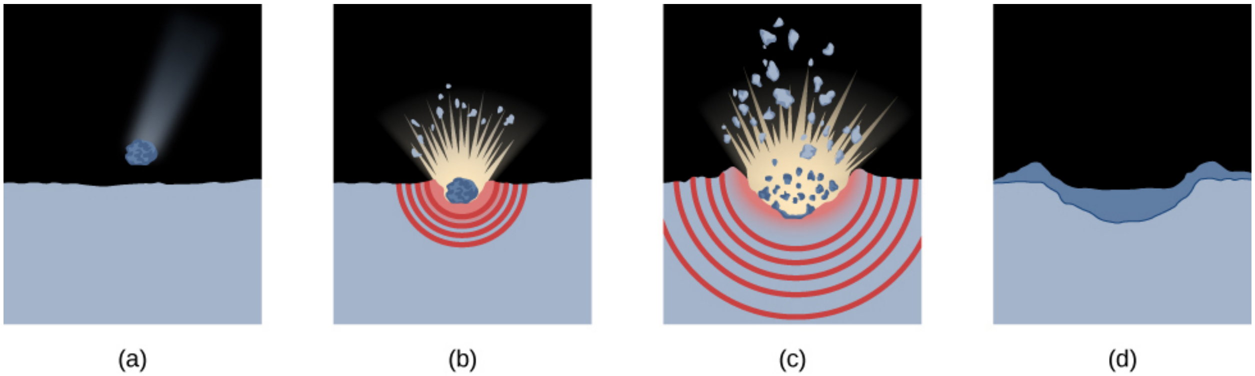

Figure 9.14 Stages in the Formation of an Impact Crater. (a) The impact occurs. (b) The projectile vaporizes and a shock wave spreads through the lunar rock. (c) Ejecta are thrown out of the crater. (d) Most of the ejected material falls back to fill the crater, forming an ejecta blanket.

An impact explosion of the sort described above leads to a characteristic kind of crater, as shown in **Figure 9.15**. The central cavity is initially bowl-shaped (the word "crater" comes from the Greek word for "bowl"), but the rebound of the crust partially fills it in, producing a flat floor and sometimes creating a central peak. Around the rim, landslides create a series of terraces.

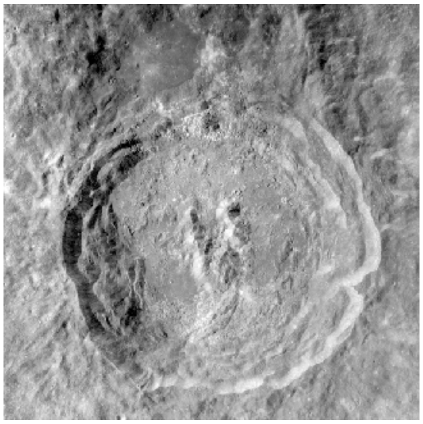

Figure 9.15 Typical Impact Crater. King Crater on the far side of the Moon, a fairly recent lunar crater 75 kilometers in diameter, shows most of the features associated with large impact structures. (credit: NASA/JSC/Arizona State University)

The rim of the crater is turned up by the force of the explosion, so it rises above both the floor and the adjacent terrain. Surrounding the rim is an *ejecta blanket* consisting of material thrown out by the explosion. This debris falls back to create a rough, hilly region, typically about as wide as the crater diameter. Additional, higher-speed ejecta fall at greater distances from the crater, often digging small *secondary craters* where they strike the surface (Figure 9.9).

Some of these streams of ejecta can extend for hundreds or even thousands of kilometers from the crater, creating the bright *crater rays* that are prominent in lunar photos taken near full phase. The brightest lunar crater rays are associated with large young craters such as Kepler and Tycho.

SEEING FOR YOURSELF

Observing the Moon

The Moon is one of the most beautiful sights in the sky, and it is the only object close enough to reveal its *topography* (surface features such as mountains and valleys) without a visit from a spacecraft. A fairly small amateur telescope easily shows craters and mountains on the Moon as small as a few kilometers across.

Even as seen through a good pair of binoculars, we can observe that the appearance of the Moon's surface changes dramatically with its phase. At full phase, it shows almost no topographic detail, and you must look closely to see more than a few craters. This is because sunlight illuminates the surface straight on, and in this flat lighting, no shadows are cast. Much more revealing is the view near first or third quarter, when sunlight streams in from the side, causing topographic features to cast sharp shadows. It is almost always more rewarding to study a planetary surface under such oblique lighting, when the maximum information about surface relief can be obtained.

The flat lighting at full phase does, however, accentuate brightness contrasts on the Moon, such as those between the maria and highlands. Notice in Figure 9.16 that several of the large mare craters seem to be surrounded by white material and that the light streaks or rays that can stretch for hundreds of kilometers across the surface are clearly visible. These lighter features are ejecta, splashed out from the crater-forming impact.

Figure 9.16 Appearance of the Moon at Different Phases. (a) Illumination from the side brings craters and other topographic features into sharp relief, as seen on the far left side. (b) At full phase, there are no shadows, and it is more difficult to see such features. However, the flat lighting at full phase brings out some surface features, such as the bright rays of ejecta that stretch out from a few large young craters. (credit: modification of work by Luc Viatour)

By the way, there is no danger in looking at the Moon with binoculars or telescopes. The reflected sunlight is never bright enough to harm your eyes. In fact, the sunlit surface of the Moon has about the same brightness as a sunlit landscape of dark rock on Earth. Although the Moon looks bright in the night sky, its surface is, on average, much less reflective than Earth's, with its atmosphere and white clouds. This difference is nicely illustrated by the photo of the Moon passing in front of Earth taken from the Deep Space Climate Observatory spacecraft (**Figure 9.17**). Since the spacecraft took the image from a position inside the orbit of Earth, we see both objects fully illuminated (full Moon and full Earth). By the way, you cannot see much detail on the Moon because the exposure has been set to give a bright image of Earth, not the Moon.

Figure 9.17 The Moon Crossing the Face of Earth. In this 2015 image from the Deep Space Climate Observatory spacecraft, both objects are fully illuminated, but the Moon looks darker because it has a much lower average reflectivity than Earth. (credit: modification of work by NASA, DSCOVR EPIC team)

One interesting thing about the Moon that you can see without binoculars or telescopes is popularly called "the new Moon in the old Moon's arms." Look at the Moon when it is a thin crescent, and you can often make out the faint circle of the entire lunar disk, even though the sunlight shines on only the crescent. The rest of the disk is illuminated not by sunlight but by earthlight—sunlight reflected from Earth. The light of the full Earth on the Moon is about 50 times brighter than that of the full Moon shining on Earth.

Using Crater Counts

If a world has had little erosion or internal activity, like the Moon during the past 3 billion years, it is possible to use the number of impact craters on its surface to estimate the age of that surface. By "age" here we mean the time since a major disturbance occurred on that surface (such as the volcanic eruptions that produced the lunar maria).

We cannot directly measure the rate at which craters are being formed on Earth and the Moon, since the average interval between large crater-forming impacts is longer than the entire span of human history. Our best-known example of such a large crater, Meteor Crater in Arizona (**Figure 9.18**), is about 50,000 years old. However, the cratering rate can be estimated from the number of craters on the lunar maria or calculated from the number of potential "projectiles" (asteroids and comets) present in the solar system today. Both lines of reasoning lead to about the same estimations.

Figure 9.18 Meteor Crater. This aerial photo of Meteor Crater in Arizona shows the simple form of a meteorite impact crater. The crater's rim diameter is about 1.2 kilometers. (credit: Shane Torgerson)

For the Moon, these calculations indicate that a crater 1 kilometer in diameter should be produced about every 200,000 years, a 10-kilometer crater every few million years, and one or two 100-kilometer craters every billion years. If the cratering rate has stayed the same, we can figure out how long it must have taken to make all the craters we see in the lunar maria. Our calculations show that it would have taken several billion years. This result is similar to the age determined for the maria from radioactive dating of returned samples—3.3 to 3.8 billion years old.

The fact that these two calculations agree suggests that astronomers' original assumption was right: comets and asteroids in approximately their current numbers have been impacting planetary surfaces for billions of years. Calculations carried out for other planets (and their moons) indicate that they also have been subject to about the same number of interplanetary impacts during this time.

We have good reason to believe, however, that earlier than 3.8 billion years ago, the impact rates must have been a great deal higher. This becomes immediately evident when comparing the numbers of craters on the lunar highlands with those on the maria. Typically, there are 10 times more craters on the highlands than on a similar area of maria. Yet the radioactive dating of highland samples showed that they are only a little older than the maria, typically 4.2 billion years rather than 3.8 billion years. If the rate of impacts had been constant throughout the Moon's history, the highlands would have had to be at least 10 times older. They would thus have had to form 38 billion years ago—long before the universe itself began.

In science, when an assumption leads to an implausible conclusion, we must go back and re-examine that assumption—in this case, the constant impact rate. The contradiction is resolved if the impact rate varied over time, with a much heavier bombardment earlier than 3.8 billion years ago (**Figure 9.19**). This "heavy bombardment" produced most of the craters we see today in the highlands.

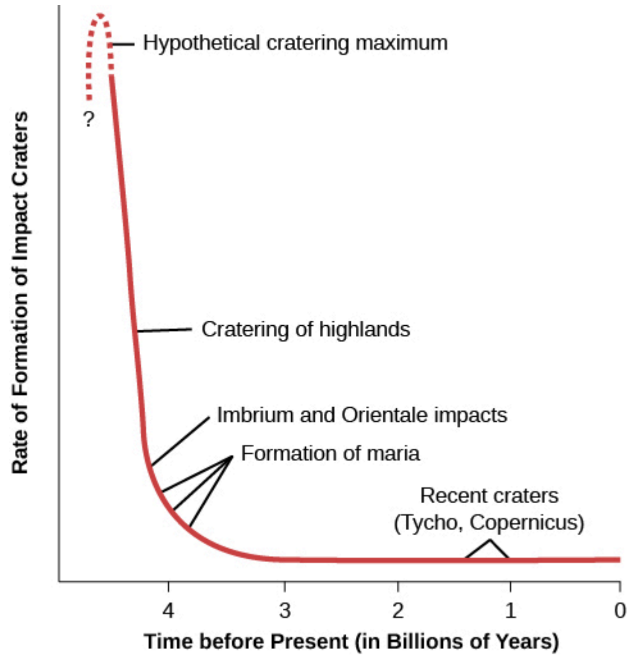

Figure 9.19 Cratering Rates over Time. The number of craters being made on the Moon's surface has varied with time over the past 4.3 billion years.

This idea we have been exploring—that large impacts (especially during the early history of the solar system) played a major role in shaping the worlds we see—is not unique to our study of the Moon. As you read through the other chapters about the planets, you will see further indications that a number of the present-day characteristics of our system may be due to its violent past.

9.4 THE ORIGIN OF THE MOON

Learning Objectives

By the end of this section, you will be able to:

- Describe the top three early hypotheses of the formation of the Moon
- Summarize the current "giant impact" concept of how the Moon formed

It is characteristic of modern science to ask how things originated. Understanding the origin of the Moon has proven to be challenging for planetary scientists, however. Part of the difficulty is simply that we know so much about the Moon (quite the opposite of our usual problem in astronomy). As we will see, one key problem is that the Moon is both tantalizingly similar to Earth and frustratingly different.

Ideas for the Origin of the Moon

Most of the earlier hypotheses for the Moon's origin followed one of three general ideas:

1. The fission theory—the Moon was once part of Earth, but somehow separated from it early in their history.
2. The sister theory—the Moon formed together with (but independent of) Earth, as we believe many moons of the outer planets formed.
3. The capture theory—the Moon formed elsewhere in the solar system and was captured by Earth.

Unfortunately, there seem to be fundamental problems with each of these ideas. Perhaps the easiest hypothesis to reject is the capture theory. Its primary drawback is that no one knows of any way that early Earth could have captured such a large moon from elsewhere. One body approaching another cannot go into orbit around it without a substantial loss of energy; this is the reason that spacecraft destined to orbit other planets are equipped with retro-rockets. Furthermore, if such a capture did take place, the captured object would go into a very eccentric orbit rather than the nearly circular orbit our Moon occupies today. Finally, there are too many compositional similarities between Earth and the Moon, particularly an identical fraction of the major isotopes[2] of oxygen, to justify seeking a completely independent origin.

The fission hypothesis, which states that the Moon separated from Earth, was suggested in the late nineteenth century. Modern calculations have shown that this sort of spontaneous fission or splitting is impossible. Furthermore, it is difficult to understand how a Moon made out of terrestrial material in this way could have developed the many distinctive chemical differences now known to characterize our neighbor.

Scientists were therefore left with the sister hypothesis—that the Moon formed alongside Earth—or with some modification of the fission hypothesis that can find a more acceptable way for the lunar material to have separated from Earth. But the more we learned about our Moon, the less these old ideas seem to fit the bill.

The Giant Impact Hypothesis

In an effort to resolve these apparent contradictions, scientists developed a fourth hypothesis for the origin of the Moon, one that involves a giant impact early in Earth's history. There is increasing evidence that large chunks of material—objects of essentially planetary mass—were orbiting in the inner solar system at the time that the terrestrial planets formed. The giant impact hypothesis envisions Earth being struck obliquely by an object approximately one-tenth Earth's mass—a "bullet" about the size of Mars. This is very nearly the largest impact Earth could experience without being shattered.

Such an impact would disrupt much of Earth and eject a vast amount of material into space, releasing almost enough energy to break the planet apart. Computer simulations indicate that material totaling several percent of Earth's mass could be ejected in such an impact. Most of this material would be from the stony mantles of Earth and the impacting body, not from their metal cores. This ejected rock vapor then cooled and formed a ring of material orbiting Earth. It was this ring that ultimately condensed into the Moon.

While we do not have any current way of showing that the giant impact hypothesis is the correct model of the Moon's origin, it does offer potential solutions to most of the major problems raised by the chemistry of the Moon. First, since the Moon's raw material is derived from the mantles of Earth and the projectile, the absence of metals is easily understood. Second, most of the volatile elements would have been lost during the high-temperature phase following the impact, explaining the lack of these materials on the Moon. Yet, by making the Moon primarily of terrestrial mantle material, it is also possible to understand similarities such as identical abundances of various oxygen isotopes.

9.5 MERCURY

Learning Objectives

By the end of this section, you will be able to:

- Characterize the orbit of Mercury around the Sun
- Describe Mercury's structure and composition

2 Remember from the Radiation and Spectra chapter that the term isotope means a different "version" of an element. Specifically, different isotopes of the same element have equal numbers of protons but different numbers of neutrons (as in carbon-12 versus carbon-14.)

- Explain the relationship between Mercury's orbit and rotation
- Describe the topography and features of Mercury's surface
- Summarize our ideas about the origin and evolution of Mercury

The planet Mercury is similar to the Moon in many ways. Like the Moon, it has no atmosphere, and its surface is heavily cratered. As described later in this chapter, it also shares with the Moon the likelihood of a violent birth.

Mercury's Orbit

Mercury is the nearest planet to the Sun, and, in accordance with Kepler's third law, it has the shortest period of revolution about the Sun (88 of our days) and the highest average orbital speed (48 kilometers per second). It is appropriately named for the fleet-footed messenger god of the Romans. Because Mercury remains close to the Sun, it can be difficult to pick out in the sky. As you might expect, it's best seen when its eccentric orbit takes it as far from the Sun as possible.

The semimajor axis of Mercury's orbit—that is, the planet's average distance from the Sun—is 58 million kilometers, or 0.39 AU. However, because its orbit has the high eccentricity of 0.206, Mercury's actual distance from the Sun varies from 46 million kilometers at perihelion to 70 million kilometers at aphelion (the ideas and terms that describe orbits were introduced in **Orbits and Gravity**).

Composition and Structure

Mercury's mass is one-eighteenth that of Earth, making it the smallest terrestrial planet. Mercury is the smallest planet (except for the dwarf planets), having a diameter of 4878 kilometers, less than half that of Earth. Mercury's density is 5.4 g/cm^3, much greater than the density of the Moon, indicating that the composition of those two objects differs substantially.

Mercury's composition is one of the most interesting things about it and makes it unique among the planets. Mercury's high density tells us that it must be composed largely of heavier materials such as metals. The most likely models for Mercury's interior suggest a metallic iron-nickel core amounting to 60% of the total mass, with the rest of the planet made up primarily of silicates. The core has a diameter of 3500 kilometers and extends out to within 700 kilometers of the surface. We could think of Mercury as a metal ball the size of the Moon surrounded by a rocky crust 700 kilometers thick (**Figure 9.20**). Unlike the Moon, Mercury does have a weak magnetic field. The existence of this field is consistent with the presence of a large metal core, and it suggests that at least part of the core must be liquid in order to generate the observed magnetic field.[3]

3 Recall from the Radiation and Spectra chapter that magnetism is an effect of moving electric charges. In atoms of metals, the outer electrons are easier to dislodge and they can form a current when the metal is in liquid form and can flow.

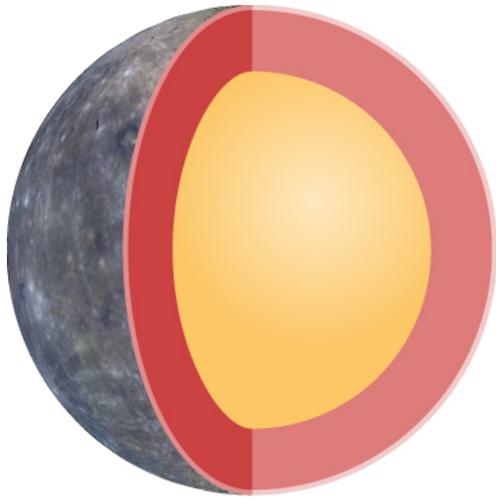

Figure 9.20 Mercury's Internal Structure. The interior of Mercury is dominated by a metallic core about the same size as our Moon.

EXAMPLE 9.1

Densities of Worlds

The average density of a body equals its mass divided by its volume. For a sphere, density is:

$$\text{density} = \frac{\text{mass}}{\frac{4}{3}\pi R^3}$$

Astronomers can measure both mass and radius accurately when a spacecraft flies by a body.

Using the information in this chapter, we can calculate the approximate average density of the Moon.

Solution

For a sphere,

$$\text{density} = \frac{\text{mass}}{\frac{4}{3}\pi R^3} = \frac{7.35 \times 10^{22}\ \text{kg}}{4.2 \times 5.2 \times 10^{18}\ \text{m}^3} = 3.4 \times 10^3\ \text{kg/m}^3$$

Table 9.1 gives a value of 3.3 g/cm^3, which is 3.3 × 10^3 kg/m^3.

Check Your Learning

Using the information in this chapter, calculate the average density of Mercury. Show your work. Does your calculation agree with the figure we give in this chapter?

Answer:

$$\text{density} = \frac{\text{mass}}{\frac{4}{3}\pi R^3} = \frac{3.3 \times 10^{23}\ \text{kg}}{4.2 \times 1.45 \times 10^{19}\ \text{m}^3} = 5.4 \times 10^3\ \text{kg/m}^3$$

That matches the value given in Table 9.1 when g/cm^3 is converted into kg/m^3.

Mercury's Strange Rotation

Visual studies of Mercury's indistinct surface markings were once thought to indicate that the planet kept one face to the Sun (as the Moon does to Earth). Thus, for many years, it was widely believed that Mercury's rotation period was equal to its revolution period of 88 days, making one side perpetually hot while the other was always cold.

Radar observations of Mercury in the mid-1960s, however, showed conclusively that Mercury does not keep one side fixed toward the Sun. If a planet is turning, one side seems to be approaching Earth while the other is moving away from it. The resulting Doppler shift spreads or broadens the precise transmitted radar-wave frequency into a range of frequencies in the reflected signal (**Figure 9.21**). The degree of broadening provides an exact measurement of the rotation rate of the planet.

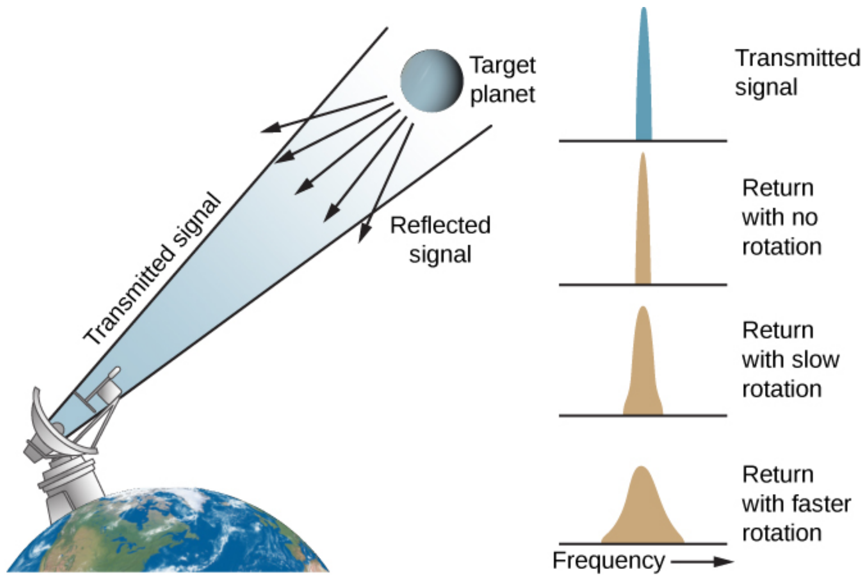

Figure 9.21 Doppler Radar Measures Rotation. When a radar beam is reflected from a rotating planet, the motion of one side of the planet's disk toward us and the other side away from us causes Doppler shifts in the reflected signal. The effect is to cause both a redshift and a blueshift, widening the spread of frequencies in the radio beam.

Mercury's period of rotation (how long it takes to turn with respect to the distant stars) is 59 days, which is just two-thirds of the planet's period of revolution. Subsequently, astronomers found that a situation where the spin and the orbit of a planet (its year) are in a 2:3 ratio turns out to be stable. (See **What a Difference a Day Makes** for more on the effects of having such a long day on Mercury.)

Mercury, being close to the Sun, is very hot on its daylight side; but because it has no appreciable atmosphere, it gets surprisingly cold during the long nights. The temperature on the surface climbs to 700 K (430 °C) at noontime. After sunset, however, the temperature drops, reaching 100 K (–170 °C) just before dawn. (It is even colder in craters near the poles that receive no sunlight at all.) The range in temperature on Mercury is thus 600 K (or 600 °C), a greater difference than on any other planet.

MAKING CONNECTIONS

What a Difference a Day Makes

Mercury rotates three times for each two orbits around the Sun. It is the only planet that exhibits this relationship between its spin and its orbit, and there are some interesting consequences for any observers who might someday be stationed on the surface of Mercury.

Here on Earth, we take for granted that days are much shorter than years. Therefore, the two astronomical ways of defining the local “day”—how long the planet takes to rotate and how long the Sun takes to return to the same position in the sky—are the same on Earth for most practical purposes. But this is not the case on Mercury. While Mercury rotates (spins once) in 59 Earth days, the time for the Sun to return to the same place in Mercury’s sky turns out to be two Mercury years, or 176 Earth days. (Note that this result is not intuitively obvious, so don’t be upset if you didn’t come up with it.) Thus, if one day at noon a Mercury explorer suggests to her companion that they should meet at noon the next day, this could mean a very long time apart!

To make things even more interesting, recall that Mercury has an eccentric orbit, meaning that its distance from the Sun varies significantly during each mercurian year. By Kepler’s law, the planet moves fastest in its orbit when closest to the Sun. Let’s examine how this affects the way we would see the Sun in the sky during one 176-Earth-day cycle. We’ll look at the situation as if we were standing on the surface of Mercury in the center of a giant basin that astronomers call Caloris (Figure 9.23).

At the location of Caloris, Mercury is most distant from the Sun at sunrise; this means the rising Sun looks smaller in the sky (although still more than twice the size it appears from Earth). As the Sun rises higher and higher, it looks bigger and bigger; Mercury is now getting closer to the Sun in its eccentric orbit. At the same time, the apparent motion of the Sun slows down as Mercury’s faster motion in orbit begins to catch up with its rotation.

At noon, the Sun is now three times larger than it looks from Earth and hangs almost motionless in the sky. As the afternoon wears on, the Sun appears smaller and smaller, and moves faster and faster in the sky. At sunset, a full Mercury year (or 88 Earth days after sunrise), the Sun is back to its smallest apparent size as it dips out of sight. Then it takes another Mercury year before the Sun rises again. (By the way, sunrises and sunsets are much more sudden on Mercury, since there is no atmosphere to bend or scatter the rays of sunlight.)

Astronomers call locations like the Caloris Basin the “hot longitudes” on Mercury because the Sun is closest to the planet at noon, just when it is lingering overhead for many Earth days. This makes these areas the hottest places on Mercury.

We bring all this up not because the exact details of this scenario are so important but to illustrate how many of the things we take for granted on Earth are not the same on other worlds. As we’ve mentioned before, one of the best things about taking an astronomy class should be ridding you forever of any “Earth chauvinism” you might have. The way things are on our planet is just one of the many ways nature can arrange reality.

The Surface of Mercury

The first close-up look at Mercury came in 1974, when the US spacecraft Mariner 10 passed 9500 kilometers from the surface of the planet and transmitted more than 2000 photographs to Earth, revealing details with a resolution down to 150 meters. Subsequently, the planet was mapped in great detail by the MESSENGER spacecraft, which was launched in 2004 and made multiple flybys of Earth, Venus, and Mercury before settling into orbit around Mercury in 2011. It ended its life in 2015, when it was commanded to crash into the surface of the planet.

Mercury’s surface strongly resembles the Moon in appearance (**Figure 9.22** and **Figure 9.23**). It is covered with thousands of craters and larger basins up to 1300 kilometers in diameter. Some of the brighter craters are rayed, like Tycho and Copernicus on the Moon, and many have central peaks. There are also *scarps* (cliffs) more than a kilometer high and hundreds of kilometers long, as well as ridges and plains.

MESSENGER instruments measured the surface composition and mapped past volcanic activity. One of its most important discoveries was the verification of water ice (first detected by radar) in craters near the poles, similar to the situation on the Moon, and the unexpected discovery of organic (carbon-rich) compounds mixed with the water ice.

LINK TO LEARNING

Scientists working with data from the **MESSENGER mission (https://openstax.org/l/30MESSmercuryrt)** put together a rotating globe of Mercury, in false color, showing some of the variations in the composition of the planet’s surface. You can watch it spin.

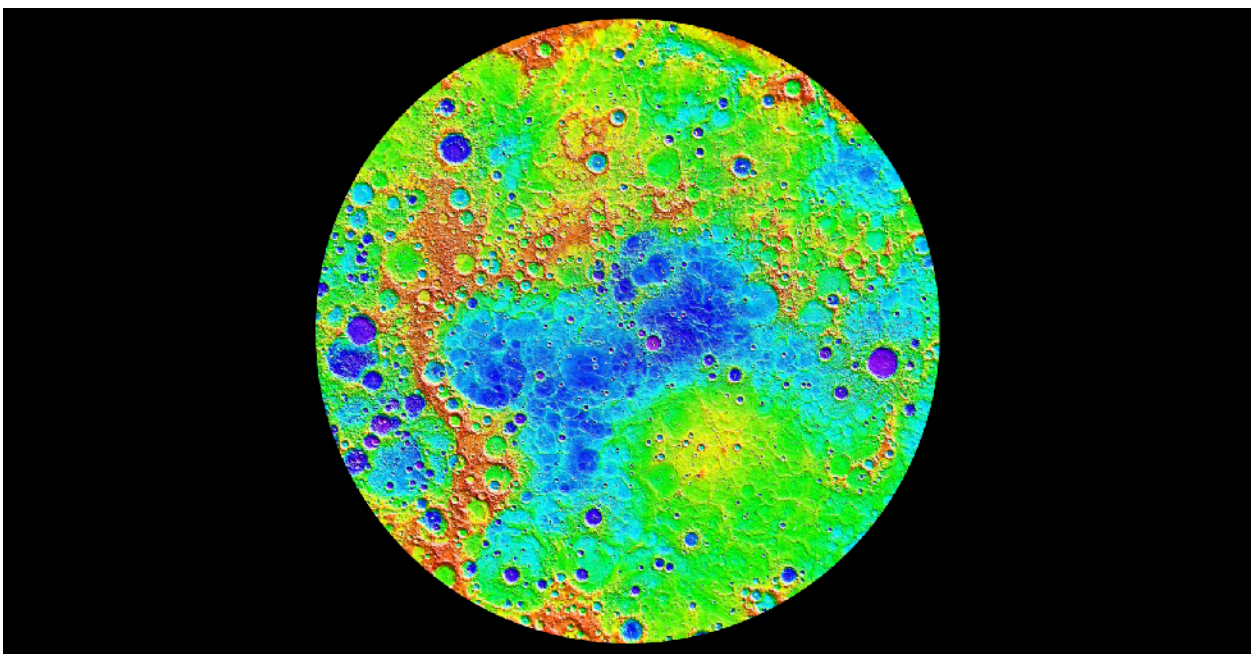

Figure 9.22 Mercury’s Topography. The topography of Mercury’s northern hemisphere is mapped in great detail from MESSENGER data. The lowest regions are shown in purple and blue, and the highest regions are shown in red. The difference in elevation between the lowest and highest regions shown here is roughly 10 kilometers. The permanently shadowed low-lying craters near the north pole contain radar-bright water ice. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington)

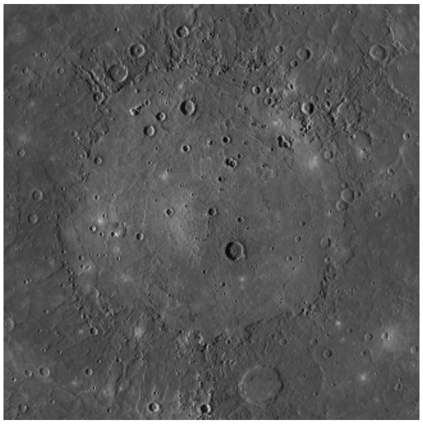

Figure 9.23 Caloris Basin. This partially flooded impact basin is the largest known structural feature on Mercury. The smooth plains in the interior of the basin have an area of almost two million square kilometers. Compare this photo with **Figure 9.11**, the Orientale Basin on the Moon. (credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington)

Most of the mercurian features have been named in honor of artists, writers, composers, and other contributors to the arts and humanities, in contrast with the scientists commemorated on the Moon. Among the named craters are Bach, Shakespeare, Tolstoy, Van Gogh, and Scott Joplin.

There is no evidence of plate tectonics on Mercury. However, the planet's distinctive long scarps can sometimes be seen cutting across craters; this means the scarps must have formed later than the craters (**Figure 9.24**). These long, curved cliffs appear to have their origin in the slight compression of Mercury's crust. Apparently, at some point in its history, the planet shrank, wrinkling the crust, and it must have done so after most of the craters on its surface had already formed.

If the standard cratering chronology applies to Mercury, this shrinkage must have taken place during the last 4 billion years and not during the solar system's early period of heavy bombardment.

Figure 9.24 Discovery Scarp on Mercury. This long cliff, nearly 1 kilometer high and more than 100 kilometers long, cuts across several craters. Astronomers conclude that the compression that made "wrinkles" like this in the planet's surface must have taken place after the craters were formed. (credit: modification of work by NASA/JPL/Northwestern University)

The Origin of Mercury

The problem with understanding how Mercury formed is the reverse of the problem posed by the composition of the Moon. We have seen that, unlike the Moon, Mercury is composed mostly of metal. However, astronomers think that Mercury should have formed with roughly the same ratio of metal to silicate as that found on Earth or Venus. How did it lose so much of its rocky material?

The most probable explanation for Mercury's silicate loss may be similar to the explanation for the Moon's lack of a metal core. Mercury is likely to have experienced several giant impacts very early in its youth, and one or more of these may have torn away a fraction of its mantle and crust, leaving a body dominated by its iron core.

LINK TO LEARNING

You can follow some of **NASA's latest research on Mercury (https://openstax.org/l/30NASAresmercu)** and see some helpful animations on the MESSENGER web page.

Today, astronomers recognize that the early solar system was a chaotic place, with the final stages of planet formation characterized by impacts of great violence. Some objects of planetary mass have been destroyed, whereas others could have fragmented and then re-formed, perhaps more than once. Both the Moon and Mercury, with their strange compositions, bear testimony to the catastrophes that must have characterized the solar system during its youth.

CHAPTER 9 REVIEW

KEY TERMS

highlands the lighter, heavily cratered regions of the Moon, which are generally several kilometers higher than the maria

mare (plural: maria) Latin for “sea;” the name applied to the dark, relatively smooth features that cover 17% of the Moon’s surface

SUMMARY

9.1 General Properties of the Moon

Most of what we know about the Moon derives from the Apollo program, including 400 kilograms of lunar samples still being intensively studied. The Moon has one-eightieth the mass of Earth and is severely depleted in both metals and volatile materials. It is made almost entirely of silicates like those in Earth’s mantle and crust. However, more recent spacecraft have found evidence of a small amount of water near the lunar poles, most likely deposited by comet and asteroid impacts.

9.2 The Lunar Surface

The Moon, like Earth, was formed about 4.5 billion year ago. The Moon’s heavily cratered highlands are made of rocks more than 4 billion years old. The darker volcanic plains of the maria were erupted primarily between 3.3 and 3.8 billion years ago. Generally, the surface is dominated by impacts, including continuing small impacts that produce its fine-grained soil.

9.3 Impact Craters

A century ago, Grove Gilbert suggested that the lunar craters were caused by impacts, but the cratering process was not well understood until more recently. High-speed impacts produce explosions and excavate craters 10 to 15 times the size of the impactor with raised rims, ejecta blankets, and often central peaks. Cratering rates have been roughly constant for the past 3 billion years but earlier were much greater. Crater counts can be used to derive approximate ages for geological features on the Moon and other worlds with solid surfaces.

9.4 The Origin of the Moon

The three standard hypotheses for the origin of the Moon were the fission hypothesis, the sister hypothesis, and the capture hypothesis. All have problems, and they have been supplanted by the giant impact hypothesis, which ascribes the origin of the Moon to the impact of a Mars-sized projectile with Earth 4.5 billion years ago. The debris from the impact made a ring around Earth which condensed and formed the Moon.

9.5 Mercury

Mercury is the nearest planet to the Sun and the fastest moving. Mercury is similar to the Moon in having a heavily cratered surface and no atmosphere, but it differs in having a very large metal core. Early in its evolution, it apparently lost part of its silicate mantle, probably due to one or more giant impacts. Long scarps on its surface testify to a global compression of Mercury’s crust during the past 4 billion years.

FOR FURTHER EXPLORATION

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The Moon

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Apollo Lunar Surface Journal: **http://www.hq.nasa.gov/office/pao/History/alsj/ (http://www.hq.nasa.gov/office/pao/History/alsj/)** . Information, interviews, maps, photos, video and audio clips, and much more on each of the Apollo landing missions.

Lunar & Planetary Institute: **http://www.lpi.usra.edu/lunar/missions/ (http://www.lpi.usra.edu/lunar/missions/)** . Lunar Science and Exploration web pages.

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NASA’s Guide to Moon Missions and Information: **http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html (http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html)** .

Origin of the Moon: **http://www.psi.edu/projects/moon/moon.html (http://www.psi.edu/projects/moon/moon.html)** . By William Hartmann, who, with a colleague, first suggested the giant impact hypothesis for how the Moon formed, in 1975.

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To the Moon: **http://www.pbs.org/wgbh/nova/tothemoon/ (http://www.pbs.org/wgbh/nova/tothemoon/)** . PBS program on the Apollo landings.

We Choose the Moon: **http://wechoosethemoon.org/ (http://wechoosethemoon.org/)** . A recreation of the Apollo 11 mission.

Mercury

Mercury Unveiled by G. Jeffrey Taylor (summarizing the Mariner 10 Mission): **http://www.psrd.hawaii.edu/Jan97/MercuryUnveiled.html (http://www.psrd.hawaii.edu/Jan97/MercuryUnveiled.html)** .

MESSENGER Mission Website: **http://messenger.jhuapl.edu/ (http://messenger.jhuapl.edu/)** .

NASA Planetary Data Center Mercury Page: **http://nssdc.gsfc.nasa.gov/planetary/planets/mercurypage.html (http://nssdc.gsfc.nasa.gov/planetary/planets/mercurypage.html)** .

Views of the Solar System Mercury Page: **http://solarviews.com/eng/mercury.htm (http://solarviews.com/eng/mercury.htm)** .

COLLABORATIVE GROUP ACTIVITIES

A. We mentioned that no nation on Earth now has the capability to send a human being to the Moon, even though the United States once sent 12 astronauts to land there. What does your group think about this?

Should we continue the exploration of space with human beings? Should we put habitats on the Moon? Should we go to Mars? Does humanity have a "destiny in space?" Whatever your answer to these questions, make a list of the arguments and facts that support your position.

B. When they hear about the giant impact hypothesis for the origin of the Moon, many students are intrigued and wonder why we can't cite more evidence for it. In your group, make a list of reasons we cannot find any traces on Earth of the great impact that formed the Moon?

C. We discussed that the ice (mixed into the soil) that is found on the Moon was most likely delivered by comets. Have your group make a list of all the reasons the Moon would not have any ice of its own left over from its early days.

D. Can your group make a list of all the things that would be different if Earth had no Moon? Don't restrict your answer to astronomy and geology. Think about our calendars and moonlit romantic strolls, for example. (You may want to review **Earth, Moon, and Sky**.)

E. If, one day, humanity decides to establish a colony on the Moon, where should we put it? Make a list of the advantages and disadvantages of locating such a human habitat on the near side, the far side, or at the poles. What site would be best for doing visible-light and radio astronomy from observatories on the Moon?

F. A member of the class (but luckily, not a member of your group) suggests that he has always dreamed of building a vacation home on the planet Mercury. Can your group make a list of all reasons such a house would be hard to build and keep in good repair?

G. As you've read in this chapter, craters on the Moon are (mostly) named after scientists. (See the official list at: http://planetarynames.wr.usgs.gov/SearchResults?target=MOON&featureType=Crater,%20craters). The craters on Mercury, on the other hand, are named for writers, artists, composers, and others in the humanities. See the official list at: http://planetarynames.wr.usgs.gov/SearchResults?target=MERCURY&featureType=Crater,%20craters). Living persons are not eligible. Can each person in your group think of a scientist or someone in the arts whom they especially respect? Now check to see if they are listed. Are there scientists or people in the arts who should have their names on the Moon or Mercury and do not?

H. Imagine that a distant relative, hearing you are taking an astronomy course, calls you up and tells you that NASA faked the Moon landings. His most significant argument is that all the photos of the Moon show black skies, but none of them have any stars showing. This proves that the photos were taken against a black backdrop in a studio and not on the Moon. Based on your reading in this chapter, what arguments can your group come up with to rebut this idea?

EXERCISES

Review Questions

1. What is the composition of the Moon, and how does it compare to the composition of Earth? Of Mercury?

2. Why does the Moon not have an atmosphere?

3. What are the principal features of the Moon observable with the unaided eye?

4. Frozen water exists on the lunar surface primarily in which location? Why?

5. Outline the main events in the Moon's geological history.

6. What are the maria composed of? Is this material found elsewhere in the solar system?

7. The mountains on the Moon were formed by what process?

8. With no wind or water erosion of rocks, what is the mechanism for the creation of the lunar "soil?"

9. What differences did Grove K. Gilbert note between volcanic craters on Earth and lunar craters?

10. Explain how high-speed impacts form circular craters. How can this explanation account for the various characteristic features of impact craters?

11. Explain the evidence for a period of heavy bombardment on the Moon about 4 billion years ago.

12. How did our exploration of the Moon differ from that of Mercury (and the other planets)?

13. Summarize the four main hypotheses for the origin of the Moon.

14. What are the difficulties with the capture hypothesis of the Moon's origin?

15. What is the main consequence of Mercury's orbit being so highly eccentric?

16. Describe the basic internal structure of Mercury.

17. How was the rotation rate of Mercury determined?

18. What is the relationship between Mercury's rotational period and orbital period?

19. The features of Mercury are named in honor of famous people in which fields of endeavor?

20. What do our current ideas about the origins of the Moon and Mercury have in common? How do they differ?

Thought Questions

21. One of the primary scientific objectives of the Apollo program was the return of lunar material. Why was this so important? What can be learned from samples? Are they still of value now?

22. Apollo astronaut David Scott dropped a hammer and a feather together on the Moon, and both reached the ground at the same time. What are the two distinct advantages that this experiment on the Moon had over the same kind of experiment as performed by Galileo on Earth?

23. Galileo thought the lunar maria might be seas of water. If you had no better telescope than the one he had, could you demonstrate that they are not composed of water?

24. Why did it take so long for geologists to recognize that the lunar craters had an impact origin rather than a volcanic one?

25. How might a crater made by the impact of a comet with the Moon differ from a crater made by the impact of an asteroid?

26. Why are the lunar mountains smoothly rounded rather than having sharp, pointed peaks (as they were almost always depicted in science-fiction illustrations and films before the first lunar landings)?

27. The lunar highlands have about ten times more craters in a given area than do the maria. Does this mean that the highlands are 10 times older? Explain your reasoning.

28. At the end of the section on the lunar surface, your authors say that lunar night and day each last about two Earth weeks. After looking over the information in **Earth, Moon, and Sky** and this chapter about the motions of the Moon, can you explain why? (It helps to draw a diagram for yourself.)

29. Give several reasons Mercury would be a particularly unpleasant place to build an astronomical observatory.

30. If, in the remote future, we establish a base on Mercury, keeping track of time will be a challenge. Discuss how to define a year on Mercury, and the two ways to define a day. Can you come up with ways that humans raised on Earth might deal with time cycles on Mercury?

31. The Moon has too little iron, Mercury too much. How can both of these anomalies be the result of giant impacts? Explain how the same process can yield such apparently contradictory results.

Figuring For Yourself

32. In the future, astronomers discover a solid moon around a planet orbiting one of the nearest stars. This moon has a diameter of 1948 km and a mass of 1.6×10^{22} kg. What is its density?

33. The Moon was once closer to Earth than it is now. When it was at half its present distance, how long was its period of revolution? (See **Orbits and Gravity** for the formula to use.)

34. Astronomers believe that the deposit of lava in the giant mare basins did not happen in one flow but in many different eruptions spanning some time. Indeed, in any one mare, we find a variety of rock ages, typically spanning about 100 million years. The individual lava flows as seen in Hadley Rille by the Apollo 15 astronauts were about 4 m thick. Estimate the average time interval between the beginnings of successive lava flows if the total depth of the lava in the mare is 2 km.

35. The Moon requires about 1 month (0.08 year) to orbit Earth. Its distance from us is about 400,000 km (0.0027 AU). Use Kepler's third law, as modified by Newton, to calculate the mass of Earth relative to the Sun.